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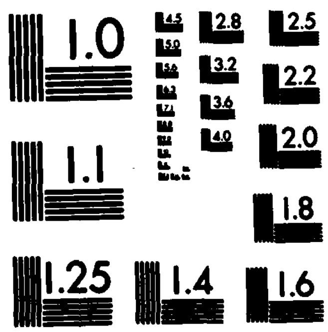

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DEVELOPMENT OF A PAVEMENT MAINTENANCE MANAGEMENT SYSTEM, VOLUME IX: DEVELOPMENT OF AIRFIELD PAVEMENT PERFORMANCE PREDICTION MODELS

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MAY 1984

FINAL REPORT
JANUARY 1980 - SEPTEMBER 1983

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ESL-TR-83-45	2. GOVT ACCESSION NO. AD-A146 150	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DEVELOPMENT OF A PAVEMENT MAINTENANCE MANAGEMENT SYSTEM, VOLUME IX: DEVELOPMENT OF AIRFIELD PAVEMENT PERFORMANCE PREDICTION MODELS		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report January 1980-September 1983
		6. PERFORMING ORG. REPORT NUMBER CERL-TR-C-76
7. AUTHOR(s) M. Y. SHAHIN, G. R. NELSON, J. M. BECKER, S. D. KOHN		8. CONTRACT OR GRANT NUMBER(s) Reimbursable Order #S-80-7
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. ARMY CONSTRUCTION ENGINEERING RESEARCH LABORATORY P.O. BOX 4005, CHAMPAIGN, IL 61820		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS PE 64708F JON 2054-4P25
11. CONTROLLING OFFICE NAME AND ADDRESS Headquarters, Air Force Engineering and Services Center (AFESC/RDCF) Tyndall AFB, Florida 32405		12. REPORT DATE May 1984
		13. NUMBER OF PAGES 188
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Availability of this report is specified on reverse of front cover.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

data collection
prediction models
pavement maintenance
airfield pavement
model verification

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Extensive data were collected from 327 airfield pavement features at 12 U.S. Air Force bases. The data, which provided a wide range of information on designs, materials, traffic, and climate, were used to develop PCI and key distress prediction models for both asphalt-concrete- and jointed-concrete-surfaced pavements. Four satisfactory models were developed for predicting PCI for PCC and AC/PCC pavements, PCI for AC and AC/AC pavements, corner breaks in PCC pavements, and reflection cracking in AC/PCC pavements.

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Additional data were collected from 101 airfield pavement features at five of the Air Force bases originally surveyed to evaluate the four prediction models. The evaluation showed that the PCI prediction models are satisfactory. The reflection cracking model also provided reasonable prediction of eight pavement features. However, verification of the corner break model showed that it has a high standard deviation of prediction.

Evaluation of the models for each of the five bases showed that predictions for some of the bases were much better than others, possibly because some of the material properties, climatic factors, and traffic conditions in certain bases were not well represented in the overall model. Thus, it was concluded that localized modeling could provide much more accurate predictions.

PREFACE

This research was performed by the U.S. Army Construction Engineering Research Laboratory (CERL), Champaign, IL 61820, under Reimbursable Order No. S-80-7 for the Air Force Engineering and Services Center, Engineering and Services Laboratory, Tyndall AFB, Florida.

This investigation was performed between January 1980 and September 1983. Dr. R. Quattrone is Chief of the Engineering and Materials Division, Colonel Paul J. Theuer was Commander and Director of CERL, and Dr. L. R. Shaffer was Technical Director. The AFESC/RDCF Project Officer was Mr. James Murfee.

This technical report has been reviewed and is approved for publication.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). It will be available at NTIS to the general public, including foreign nationals.

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SECTION I

INTRODUCTION

A. BACKGROUND

For several years, the U.S. Air Force has been developing and implementing an airfield pavement maintenance management system (References 1-8). The major objectives of this system are to provide the capability to (1) select the most cost-effective maintenance and repair (M&R) alternative for a given pavement feature, and (2) predict the future performance of pavements so that long-range M&R needs can be estimated. To do this, the engineer needs analytical methods of predicting future pavement condition over a variety of M&R alternatives (e.g., routine M&R, extensive patching, or placement of an overlay).

Overall pavement condition is defined by the Pavement Condition Index (PCI) along with certain key major distress types. The PCI is a composite index that represents the pavement's structural integrity and operational surface condition (References 1-5). By predicting the PCI and the distress over a future time period, the user can determine the consequences of various M&R alternatives and how long it will be until major M&R is needed.

In FY 77, preliminary research to develop analytical methods of predicting pavement condition led to the conclusion that it was feasible to predict pavement condition using empirical regression models developed from field data and mathematical methods (Reference 4). During FY 78 and FY 79, preliminary prediction models were developed, using data collected from field surveys. This produced four multiple-regression models:

1. PCI prediction for jointed concrete with and without asphalt or concrete overlays

2. PCI prediction for flexible pavement with and without flexible overlays

3. Slab cracking for jointed-concrete pavement

4. Alligator cracking for flexible pavement.

These models (Reference 7) were based on a very limited amount of data, which was not believed adequate for use throughout the Air Force. However, they did clearly show that more comprehensive models could be developed if a broader data base were available, so a program for comprehensive data collection was begun in FY 80.

B. OBJECTIVE

The objectives of this study were: (1) to collect extensive data from in-service Air Force pavements over typical ranges of design materials, traffic, and climate, (2) to begin developing improved PCI and distress models for

asphalt and concrete pavements using the expanded data base, and (3) to verify the model.

C. APPROACH

Computer-coded data collection forms were prepared that would include more than 150 pieces of information from each feature. Data were collected from 327 in-service airfield pavement features located throughout the United States in 1980, providing a wide range of designs, materials and soils, traffic, and climates. The data were then checked, computer-processed, and prepared for analysis. Multiple-regression techniques were selected for developing PCI and key distress prediction models using this large data base. Additional data were then collected in 1982 from 101 previously surveyed features and used to evaluate the prediction models.

SECTION II

DATA COLLECTION FOR MODEL DEVELOPMENT

Airfield pavement data were obtained from 12 Air Force bases throughout the United States during 1980 (see Figure 1). This section describes the data collection effort.

A. DATA COLLECTION SHEETS

A set of computer-coded data collection sheets was prepared to provide uniformity and ease of data collection and processing. Initially, all known variables or those believed to affect pavement performance were considered. This list was reduced to those variables likely to be available from existing Air Force base files and those that could be estimated. The main objective was to obtain a complete historical set of information about each pavement feature, including:

1. Feature identification
2. Pavement layer information, including all overlays
3. Joint design for concrete pavements
4. Foundation soils
5. Traffic for each mission (type, annual operations)
6. Past maintenance
7. Current PCI and distress.

Appendix A provides a complete set of data collection sheets and coding sheets.

B. DATA COLLECTION PROCEDURES

Air Force bases having both asphalt and concrete pavements were selected over a range of climates and traffic. An average of 27 features was obtained for each base, for a total of 327 features. These features are divided into the following pavement types and uses:

Pavement Type	%Features
PCC	60
PCC over PCC	1
PCC over AC	1
AC	10
AC over PCC	9
AC over AC	18
Other	1
	100%

Uses	%Features
Runway	35
Taxiway	46
Apron	19
	100%

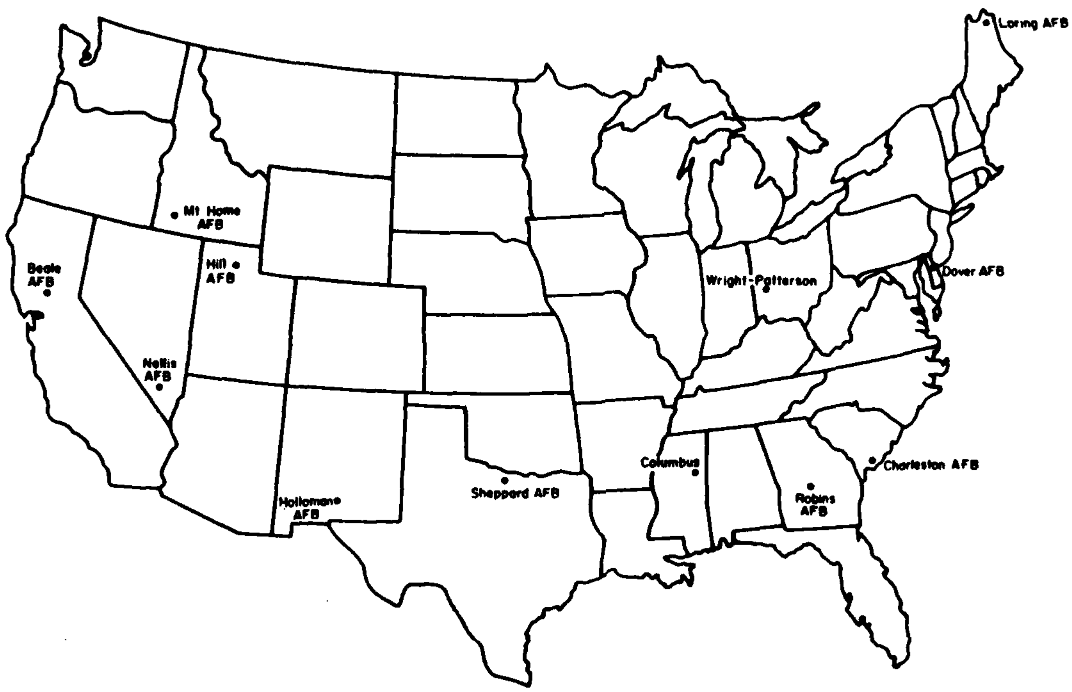

Figure 1. Geographical Spread of Data.

The data for these features were obtained from (1) Air Force pavement evaluation reports, (2) construction records in the base engineering office and other historical records, and (3) the recollections of employees about past traffic missions and current traffic flows on airfield features. Some data, such as traffic, were very difficult to obtain, but even subjective estimates were considered better than no data at all. All traffic volumes were considered as approximate only.

A number of mechanistic variables were also computed including:

1. Edge stress for concrete slabs computed by the H-51 computer program (Reference 9).

2. Radial strain at the bottom of the original asphalt layer, vertical stress on the base course, surface deflection, and vertical strain on top of the subgrade for asphalt pavement (computed by the BISAR computer program) (Reference 10).

Appendix B describes the computation of these mechanistic variables.

C. DATA PROCESSING

The data were coded on forms and then checked and computer-processed. All data sheets were carefully checked for errors and missing data. The corrected data were then keypunched onto cards and read into a computer disk file using the Statistical Package for the Social Sciences (SPSS) (Reference 11). Means, frequencies, and other statistics were obtained to further verify the reasonableness of the data. This effort was very time-consuming and costly, but insured the best possible data for developing predictive models.

D. TYPICAL MEANS AND RANGES OF VARIABLES

Tables 1 and 2 summarize the collected data variables. Tables 3 and 4 summarize the means and ranges of some key variables and computed variables. Other variables, such as slab fatigue, were also computed and used in the model development (see Section III). The predictive models are based completely on the collected data and are, therefore, limited by the ranges of the variables included in the data bank. The data represent a broad range of pavements constructed by the Air Force over the past 30 years. Figures 2 through 27 are histograms prepared for selected variables to show their overall distribution.

The following is an example of a study which can be performed using SPSS with a large data base. The life of an asphalt pavement surface before overlay was investigated. It was found that on the average, an original asphalt surface will have a life of 15.7 years before it needs overlay (see Figure 28). The reason for overlay may be a change in mission (requiring an improvement in the pavement's structural integrity) or simply that the pavement needs rehabilitation.

An asphalt pavement that has been overlaid once will have a life of 9.72 years before being overlaid for the second time, and the life of an asphalt pavement that has been overlaid twice will be an average of 7 years. This general trend suggests that on the average, an asphalt surface layer will not last as long as the underlying layer. The reason may be that asphalt overlays are underdesigned or that the damage to a previous layer is not properly accounted for, causing the newer asphalt surface to fail earlier than expected.

TABLE 1. LIST OF RAW DATA VARIABLES CONSIDERED IN THE DEVELOPMENT OF THE CONCRETE PAVEMENT PCI PREDICTION MODEL.

FTYPE	(Feature Type; Runway, Taxiway, Apron)
FWIDTH	(Feature Width) -- Feet
FLENGTH	(Feature Length) -- Feet
FAREA	(Feature Area) -- Square Feet
SURDATE*	(Original Surface Placement Date) -- Year
SURTHICK*	(Original Surface Thickness) -- Inches
SURMR*	(Original Surface Modulus of Rupture) -- PSI
BDATE**	(Base Layer Placement Date) -- Year
BMATL**	(Base Material) -- Coded
THICK**	(Base Thickness) -- Inches
BK	(K Value on Top of Base) -- Pounds/Cubic Inch
BMR	(Base Modulus of Rupture -- Cement-Stabilized Only) -- PSI
JSL	(Slab Length) -- Feet
JSW	(Slab Width) -- Feet
LJDPL	(Joint Design -- Longitudinal Paving Lane) -- Coded
TJD	(Joint Design -- Transverse) -- Coded
JFILLER	(Joint Filler -- Original) -- Coded
SGMOD	(Subgrade Modification, If Any) -- Coded
SGMATL	(Subgrade Material) -- Coded
SGK	(K Value on Top of Subgrade) -- Pounds/Cubic Inches
H2OTABLE	(Depth of Water Table) -- Feet
PMSTART	(Present Mission Starting Date) -- Year
PMSTOP***	(Present Mission Ending Date)* -- Year
PMCAT1+	(Amount of Usage Category #1 Accounts for This Pavement Feature) -- Percentage
PMANOPS++	(Number of Repetitions Per Year for This Pavement Feature) -- Percentage
CRFILL	(Overall Maintenance Policy) -- Coded
JTCRFLI	(Joint/Crack Fill Interval) -- Years
SRAREA	(Slabs Replaced) -- Percentage of Total Area
SRAGE	(Average Age of Replaced Slabs) -- Years
FI	(Average Freezing Index) -- Degree Days Below 32°F
FTC1	(Average Annual Number of Freeze-Thaw Cycles at 1-Inch Depth)
FTC2	(Average Annual Number of Freeze-Thaw Cycles at 2-Inch Depth)
FTC3	(Average Annual Number of Freeze-Thaw Cycles at 3-Inch Depth)
AAPREC	(Average Annual Precipitation) -- Inches
AATEMP	(Average Annual Temperature) -- °F
ADTR	(Average Daily Temperature Range) -- °F
AATR	(Average Annual Temperature Range) -- °F
THORMI	(Thornthwaite Moisture Index)
ADSR	(Average Daily Solar Radiation) -- Langleys
JULSR	(July Daily Solar Radiation) -- Langleys
PEVAP	(Potential Evaporation) -- Inches
OPEVAP	(Open Water Evaporation Potential) -- Inches
AAWS	(Average Annual Wind Speed) -- MPH

*Properties also recorded for concrete overlay layers.
**Properties also recorded for all subbase layers.
***This date corresponds with date PCI was taken.
+Repeated for Categories 1 through 6 (see Appendix B).
++Repeated for two previous missions if necessary.

TABLE 2. LIST OF RAW DATA VARIABLES CONSIDERED IN THE DEVELOPMENT OF THE ASPHALT PAVEMENT PCI PREDICTION MODEL.

FTYPE	(Feature Type: Runway, Taxiway, Apron)
FWIDTH	(Feature Width) -- Feet
FLENGTH	(Feature Length) -- Feet
FAREA	(Feature Area) -- Square Feet
SURDATE*	(Original Surface Placement Date) -- Year
SURPASPH	(Surface Layer Percent Asphalt)
SURAVOID	(Surface Layer Air Voids) -- Percent
SURFVOID	(Surface Layer Filler Voids) -- Percent
SURMS	(Surface Layer Marshall Stability) -- Pounds
SURFLOW	(Surface Layer Flow Measurement) -- 0.01 Inches
SURPEN	(Surface Layer Penetration) -- mm x 10^{-1}
BDATE**	(Base Layer Placement Date) -- Year
BMATL**	(Base Material) -- Coded
BTHICK**	(Base Thickness) -- Inches
BCBR**	(Base Layer CBR)
BMS**	(Base Layer Marshall Stability) -- Pounds
BDENSE**	(Base Layer Density) -- Percent of Optimum
BMOIST**	(Base Layer Moisture Content) -- Percent
JSL	(Slab Length) -- Feet
JSW	(Slab Width) -- Feet
LJDPL	(Joint Design-Longitudinal Paving Lane) -- Coded
TJD	(Joint Design - Transverse) -- Coded
JFILLER	(Joint Filler - Original) -- Coded
SGMOD	(Subgrade Modification, If Any) -- Coded
SGMATL	(Subgrade Material) -- Coded
SGCBR	(Subgrade CBR)
PI	(Plasticity Index for Subgrade)
LL	(Liquid Limit for Subgrade)
SGOPTMC	(Subgrade Optimum Moisture Content)
SGINSMC	(*In Situ* Subgrade Moisture Content)
SGDENSE	(Subgrade Density) -- Percent of Optimum
H2OTABLE	(Depth of Water Table) -- Feet
PMSTART	(Present Mission Starting Date) -- Year
PMSTOP***	(Present Mission Ending Date)* -- Year
PMCAT1+	(Amount of Usage Category #1 Accounts for this Pavement Feature) -- Percentage
PMANOPS++	(Number of Repetitions Per Year for This Pavement Feature) -- Percentage
CRFILL	(Overall Maintenance Policy) -- Coded
FI	(Freezing Index) -- Degree Days Below 32°
FTC1	(Average Annual Number of Freeze-Thaw Cycles at 1-Inch Depth)

*Properties also recorded for all overlay layers.
**Properties also recorded for all subbase layers.
***This data corresponds with date PCI was taken.
+Repeated for Categories 1 through 6.
++Repeated for two previous missions if necessary.

TABLE 2. LIST OF RAW VARIABLES CONSIDERED IN THE DEVELOPMENT OF THE ASPHALT PAVEMENT PCI PREDICTION MODEL (CONCLUDED).

FTC2	(Average Annual Number of Freeze-Thaw Cycles at 2-Inch Depth)
FTC3	(Average Annual Number of Freeze-Thaw Cycles at 3-Inch Depth)
AAPREC	(Average Annual Precipitation) -- Inches
AATEMP	(Average Annual Temperature) -- ^{o}F
ADTR	(Average Daily Temperature Range) -- ^{o}F
AATR	(Average Annual Temperature Range) -- ^{o}F
THORMI	(Thornthwaite Moisture Index)
ADSR	(Average Daily Solar Radiation) -- Langleys
JULSR	(July Daily Solar Radiation) -- Langleys
PEVAP	(Potential Evaporation) -- Inches
OPEVAP	(Open Water Evaporation Potential) -- Inches
AAWS	(Average Annual Wind Speed) -- MPH

TABLE 3. MEANS AND RANGES OF KEY CONCRETE PAVEMENT VARIABLES (162 FEATURES SAMPLED AT 12 BASES IN 1980).

	Mean Value	Range
Layer Information Variables		
Surface Age -- years	18.0	2-37
PCC Thickness -- Inches	15.3	2-24
Modulus of Rupture -- psi	701	480-992
Base Material** -- Coded*	-	-
Base Thickness** -- Inches	12.7	2-55
Subgrade Material -- Coded*	-	-
Modulus of Subgrade Reaction (K)*** -- pci	240	15-500
Environmental Variables		
Average Annual Temperature -- ^{o}F	60.0	38.8-65.8
Average Annual Precipitation -- Inches	29.7	3.8-52.1
Freezing Index -- Degree Days	127.4	0-1980
Freeze-Thaw Cycles -- 2-Inch Depth	25.8	0-111
Water Table -- Feet	100	4-500
Discrete Variables		
Feature Type -- Coded*	-	-
Crack Filling Policy -- Coded*	-	-
Primary or Secondary -- Coded*	-	-
Mechanistic Variables		
Fatigue	68430	352-612,654
Damage	425.86	0-26,420

*Means and ranges not applicable to coded variables.
**Mean value does not include those features with no base course; 68 features had no base course.
***K value on top of layer which PCC surface rests upon.

TABLE 4. MEANS AND RANGES OF KEY ASPHALT PAVEMENT VARIABLES (69 FEATURES SAMPLED AT 12 BASES IN 1980).

	Mean Value	Range
Layer Information Variables		
Surface Age -- Years	10.58	0-27
Original AC Thickness -- Inches	3.80	2.0-7.0
Total AC Thickness -- Inches	5.85	2.0-14.0
Base Material -- Coded**	-	-
Base CBR* -- Percent	85.13	20-100
Total Select Thickness -- Inches	30.62	0.0-67.0
Subgrade Material -- Coded**	-	-
Subgrade CBR -- Percent	17.80	6-88
Environmental Variables		
Average Annual Temperature -- ^{o}F	54.2	38.0-65.8
Average Annual Temperature Range -- ^{o}F	45.2	31.6-54.2
Average Daily Temperature Range -- ^{o}F	23.4	19.1-28.5
Average Annual Precipitation -- Inches	26.2	3.8-52.1
Average Annual Solar Radiation -- Langleys	407	325-520
Freezing Index -- Degree Days	491	0-1980
Freeze-Thaw Cycles -- 2-Inch Depth	26.5	0-99
Water Table -- Feet	100	4-500
Discrete Variables		
Feature Type -- Coded**	-	-
Crack Filling Policy -- Coded**	-	-
Primary or Secondary -- Coded**	-	-
Mechanistic Variables		
Weighted Average Surface Deflection (Present Period) -- (Inches/ESWL)	.001	0-.005
Weighted Average Surface Deflection*** (First Previous Period) -- (Inches/ESWL)	.001	0-.002
Weighted Average Vertical Stress on Base (Present Period) -- psi	86.2	0-175
Weighted Average Vertical Stress on Base* (First Previous Period)***	59.7	0-203
Cumulative Vertical Stress on Base (Present Period) -- (psi x No. of Passes)	1.039×10^{7}	$0-1.414 \times 10^{8}$
Cumulative Vertical Stress on Base -- (First Previous Period)***	6.841×10^{6}	$0-1.163 \times 10^{8}$
Cumulative Vertical Strain on Subgrade (Present Period) -- (0.001 Inches/Inch x No. of Passes)	6.067×10^{5}	$0-8.881 \times 10^{6}$
Cumulative Vertical Stress on Subgrade (First Previous Period)*** -- 0.001 Inches/Inch x No. of Passes)	4.771×10^{5}	$0-1.274 \times 10^{7}$

*Mean value does not include features with no base (four features have no base).

**Means and ranges not applicable to coded variables.

***A period is defined by the age of the surface or overlay. (See Figure 29.) If no overlay exists and therefore there is no previous period, the value for this variable for that particular feature is recorded as 0. These features are included in the calculation of the mean value.

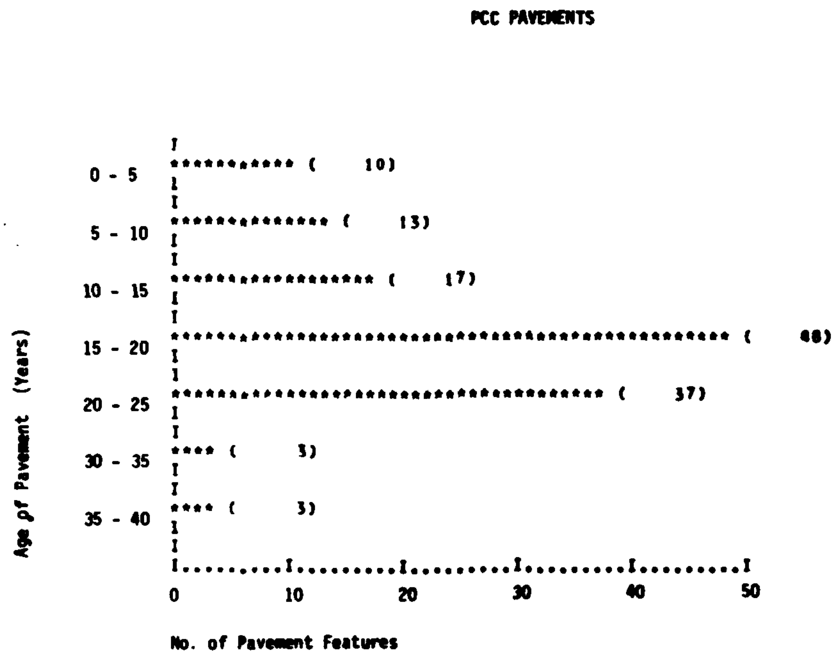

Figure 2. Histogram of PCC Pavement Age in Years Since Construction.

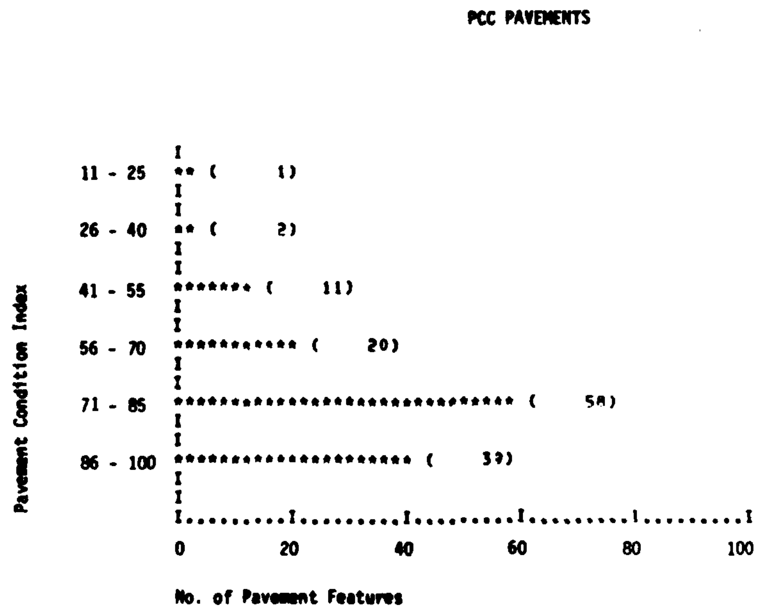

Figure 3. Histogram of PCC Pavement Feature PCI.

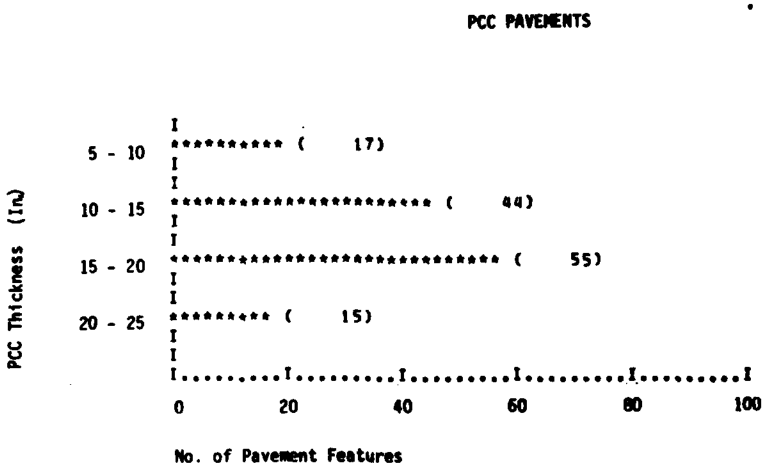

Figure 4. Histogram of PCC Surface Thickness in Inches.

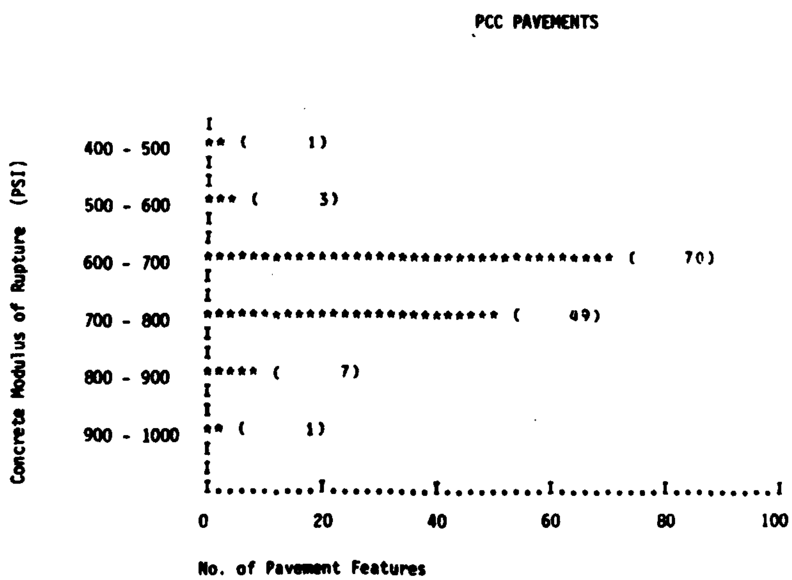

Figure 5. Histogram of Modulus of Rupture of Concrete in Pounds.

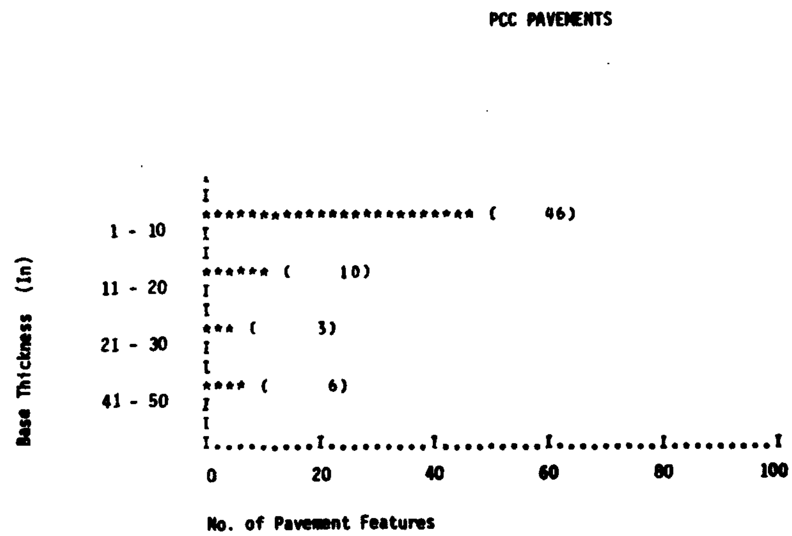

Figure 6. Histogram of PCC Pavement Base Course Thickness in Inches.

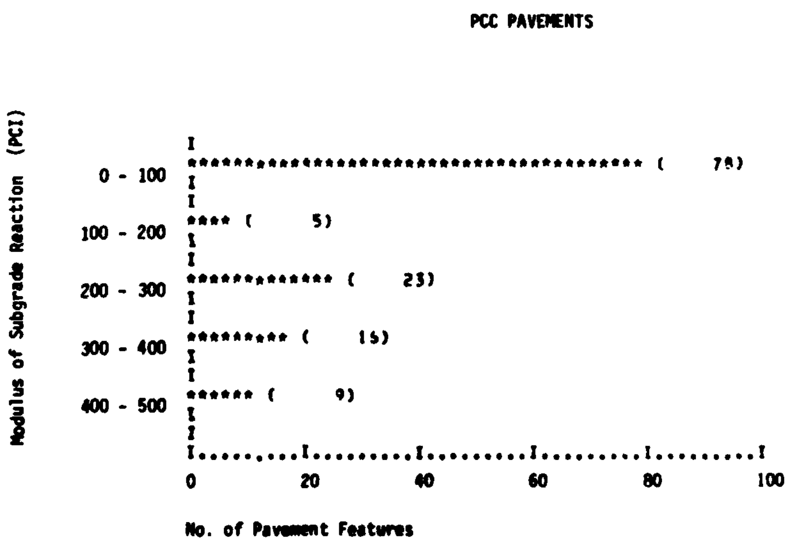

Figure 7. Histogram of PCC Pavement Modulus of Subgrade.

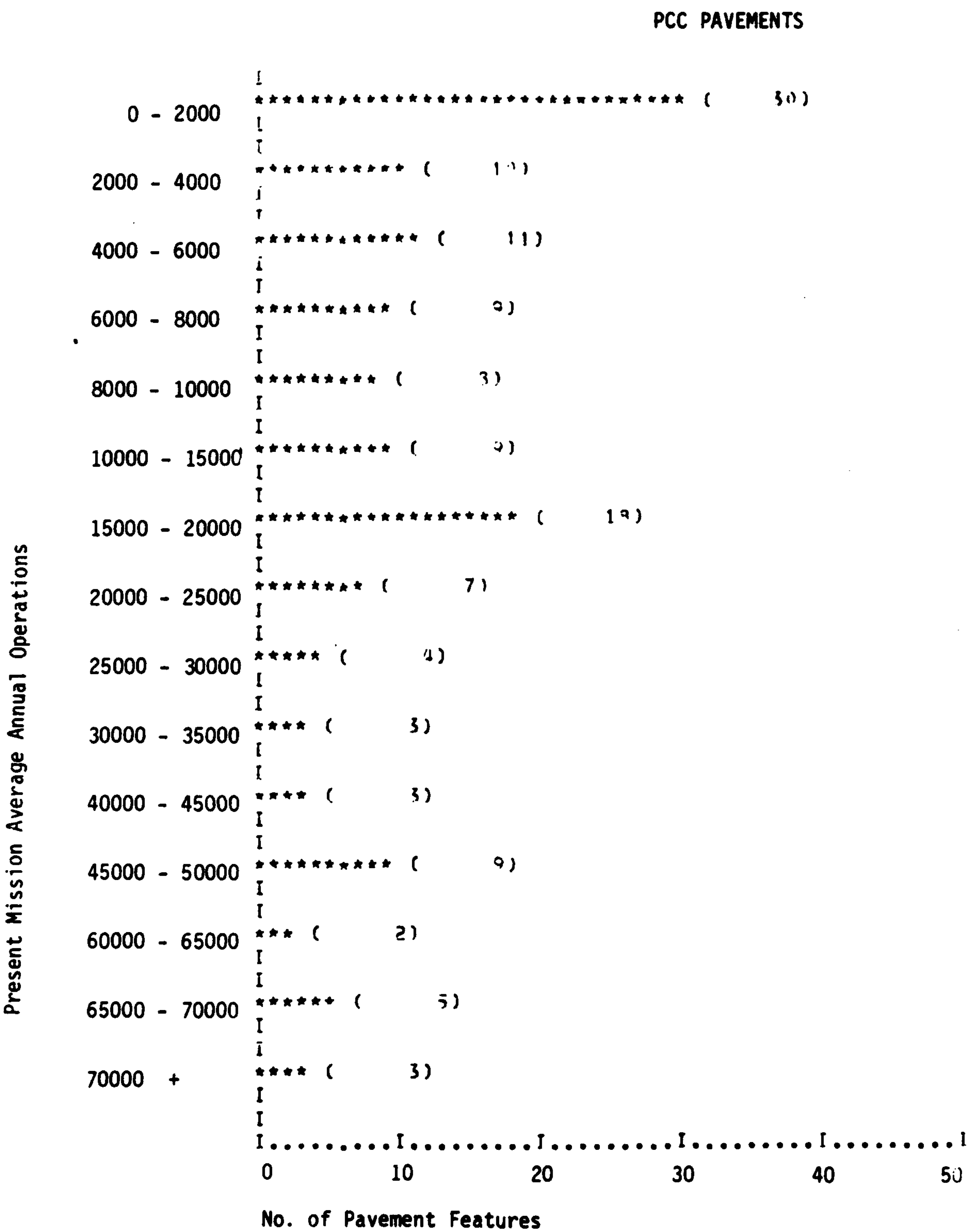

Figure 8. Histogram of Average Annual Volume of Traffic on PCC Pavement.

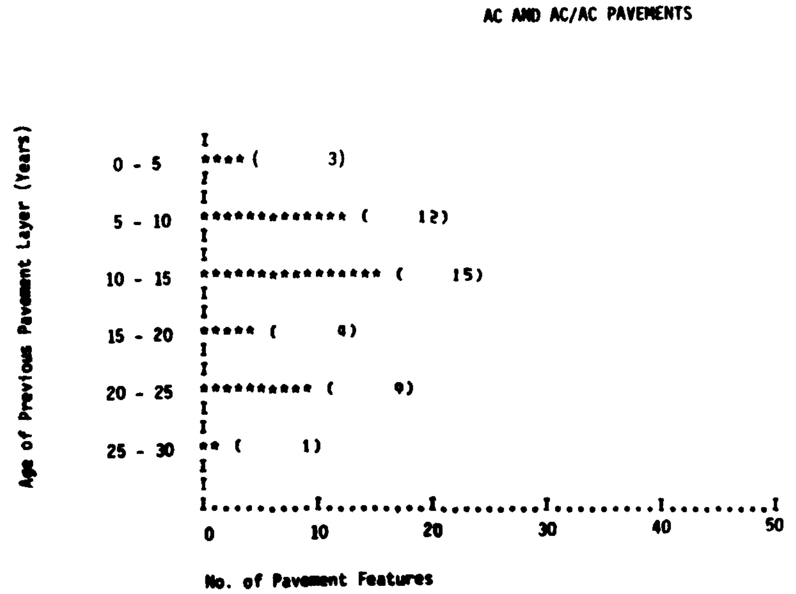

Figure 9. Histogram of AC and AC/AC Pavement Age in Years.

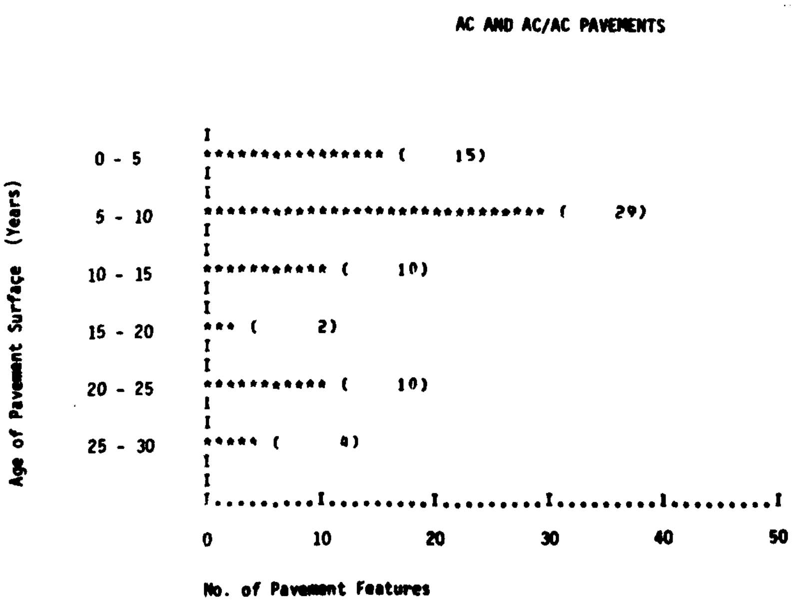

Figure 10. Histogram of Age of Previous Pavement Layer (AGECOL) in Years of AC and AC/AC Pavement. (NOTE: 26 AC Pavements Have Not Been Overlaid.)

AC AND AC/AC PAVEMENTS

```
                     I
              0      ************************** (     26)
                     I
                     I
              1      ************************** (     26)
                     I
Number of            I
Overlays      2      ************* (     13)
                     I
                     I
              3      ***** (     5)
                     I
                     I
                     I.........I.........I.........I.........I.........I
                     0         1         2         3         4         5

                     No. of Pavement Features
```

Figure 11. Histogram of AC and AC/AC Pavement Feature PCI.

AC AND AC/AC PAVEMENTS

```
                       I
             26 - 40   *** (      2)
                       I
                       I
             41 - 55   ******** (      7)
Pavement               I
Condition              I
Index        56 - 70   ****************** (      18)
                       I
                       I
             71 - 85   ****************************** (      30)
                       I
                       I
             86 - 100  ************* (      13)
                       I
                       I
                       I.........I.........I.........I.........I.........I
                       0         10        20        30        40        50

                       No. of Pavement Features
```

Figure 12. Histogram of Number of Overlays for AC and AC/AC Pavement.

AC AND AC/AC PAVEMENTS

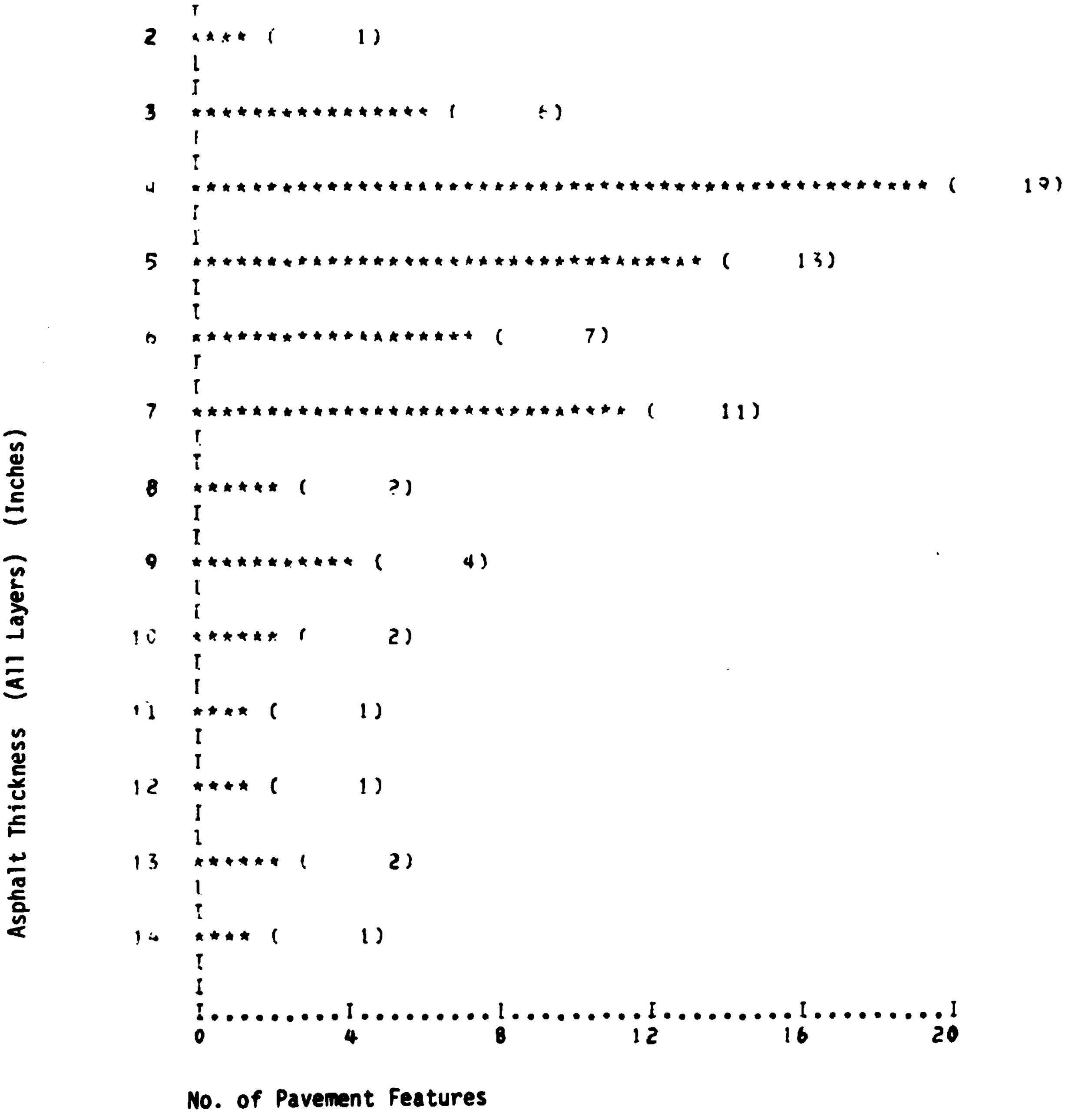

Figure 13. Histogram of AC and AC/AC Pavement Total Asphalt Thickness in Inches.

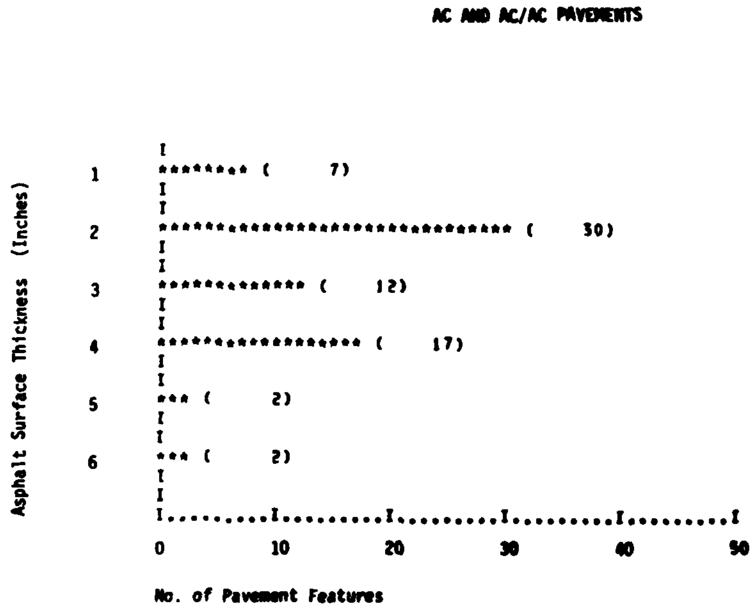

Figure 14. Histogram of AC and AC/AC Pavement Surface Thickness in Inches.

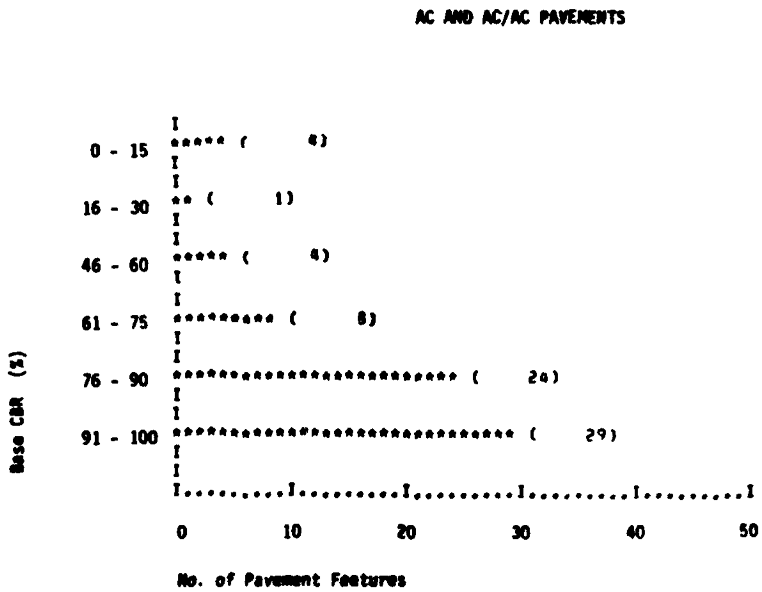

Figure 15. Histogram of AC and AC/AC Pavement Base Course California Bearing Ratio (CBR) Percent.

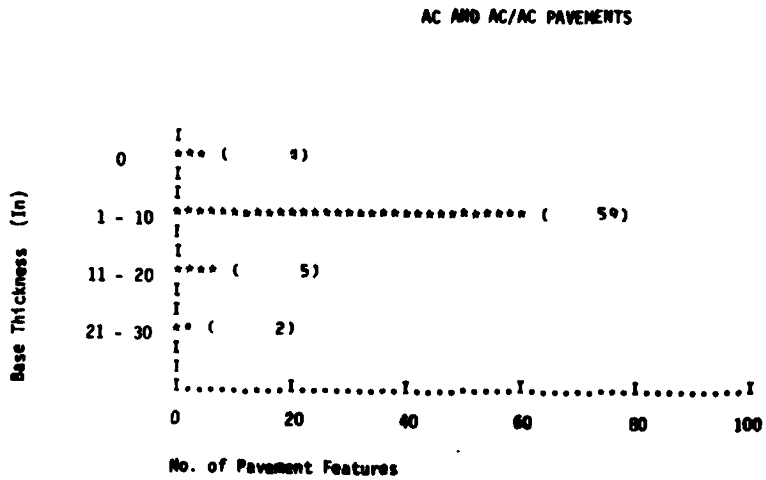

Figure 16. Histogram of AC and AC/AC Pavement Base Course Thickness in Inches.

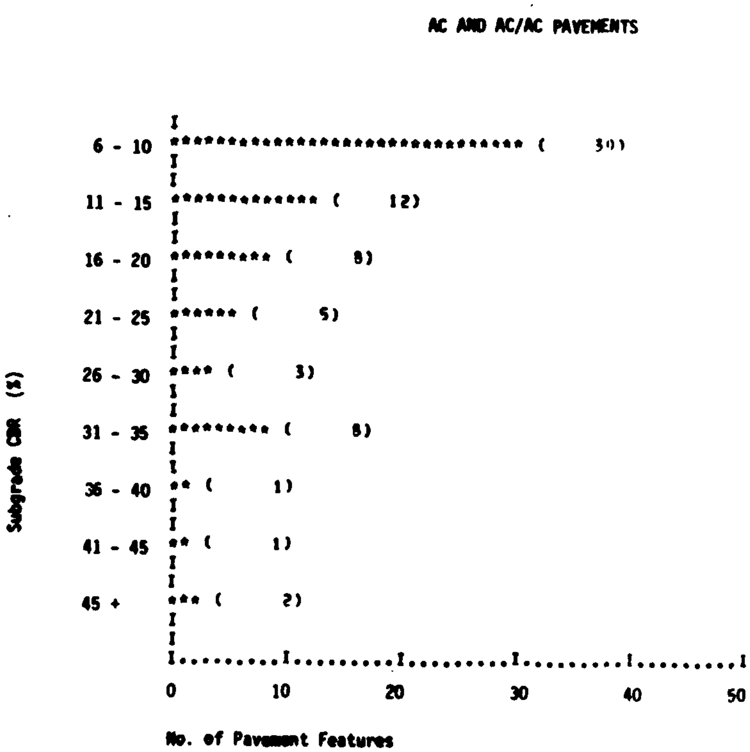

Figure 17. Histogram of AC and AC/AC Pavement Subgrade California Bearing Ratio (CBR) Percent.

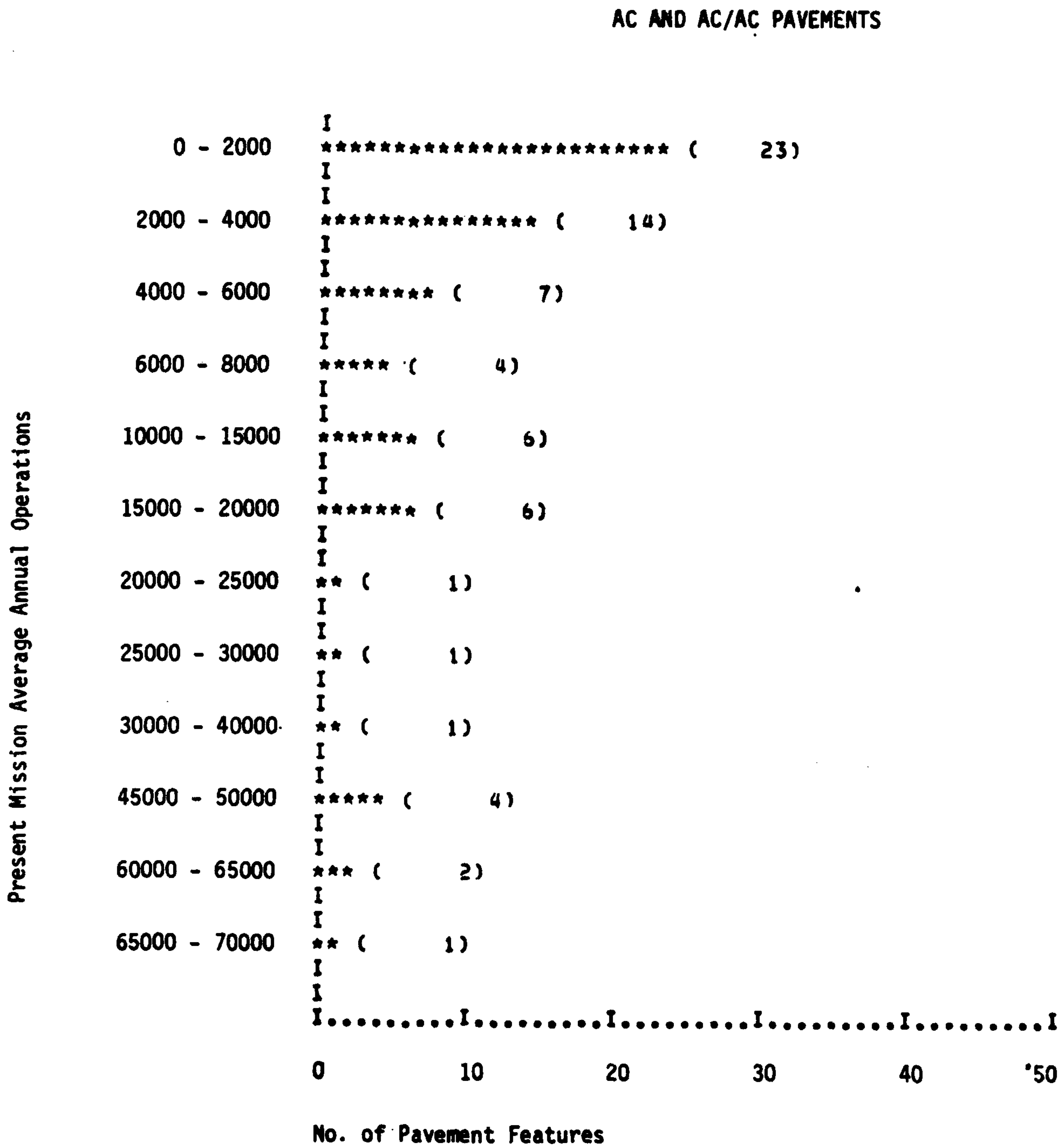

Figure 18. Histogram of Average Annual Volume of Traffic on AC and AC/AC Pavement.

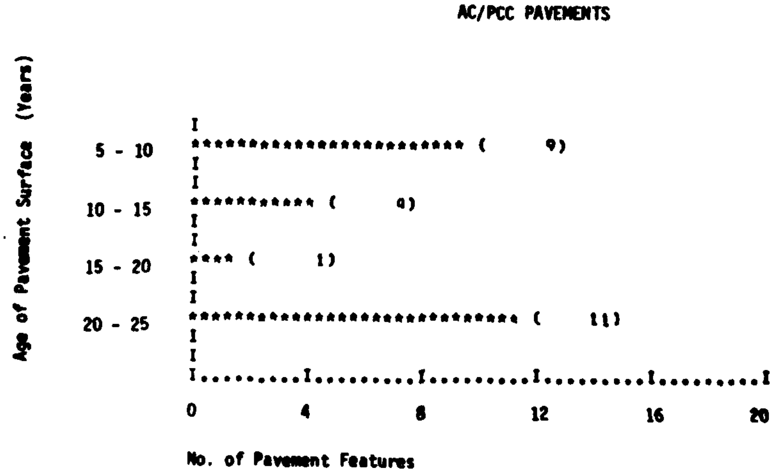

Figure 19. Histogram of AC/PCC Pavement Age in Years Since Last Overlay.

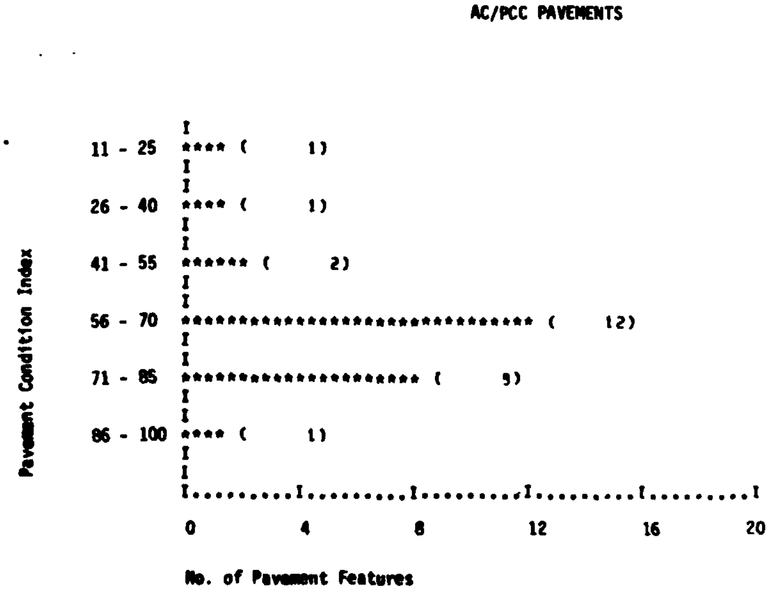

Figure 20. Histogram of AC/PCC Pavement Feature PCI.

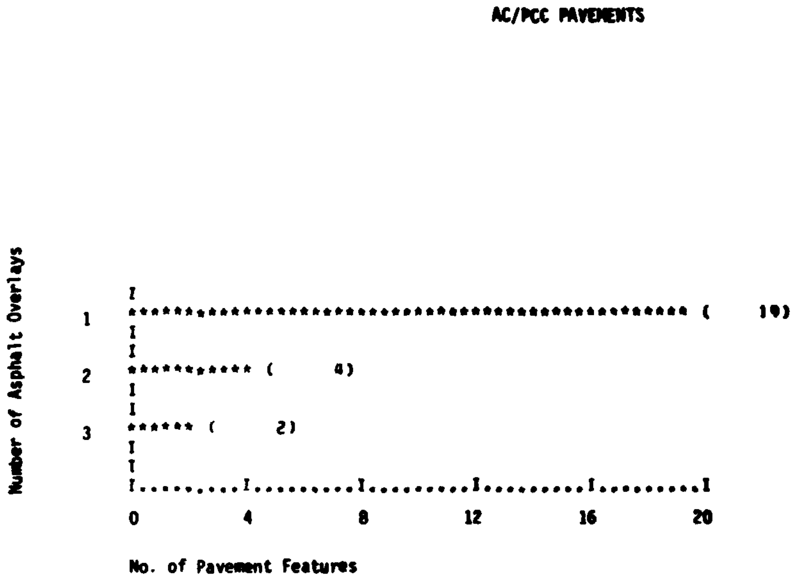

Figure 21. Histogram of Number of Asphalt Overlays for AC/PCC Pavement.

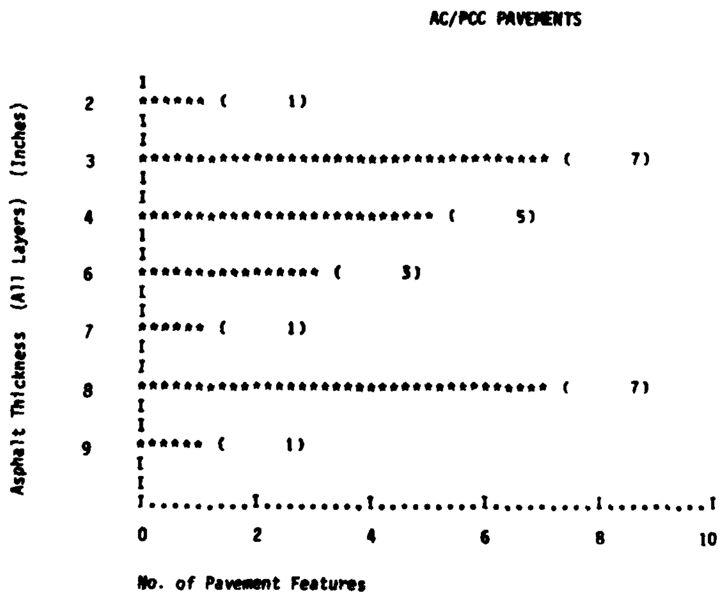

Figure 22. Histogram of AC/PCC Pavement Total Asphalt Thickness in Inches.

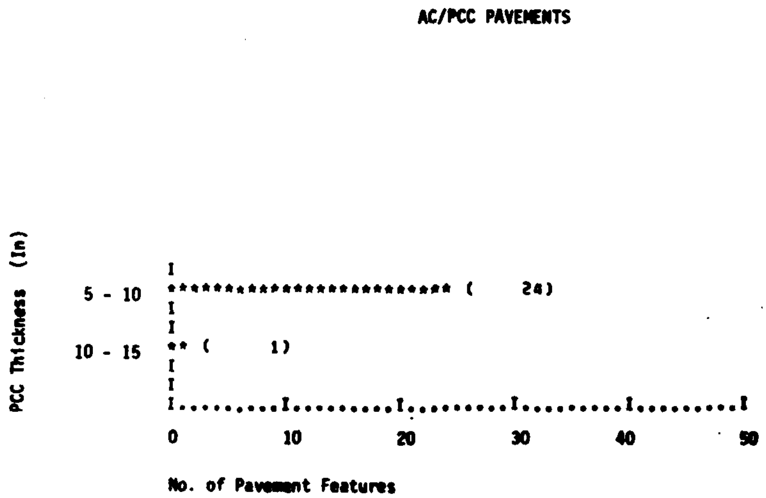

Figure 23. Histogram of AC/PCC Pavement Concrete Thickness in Inches.

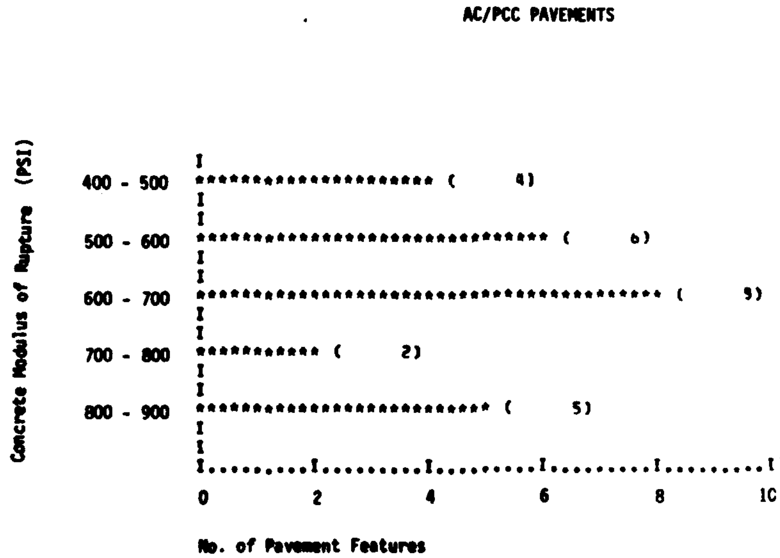

Figure 24. Histogram of Modulus of Rupture of Concrete in Pounds Per Square Inch (AC/PCC Pavement).

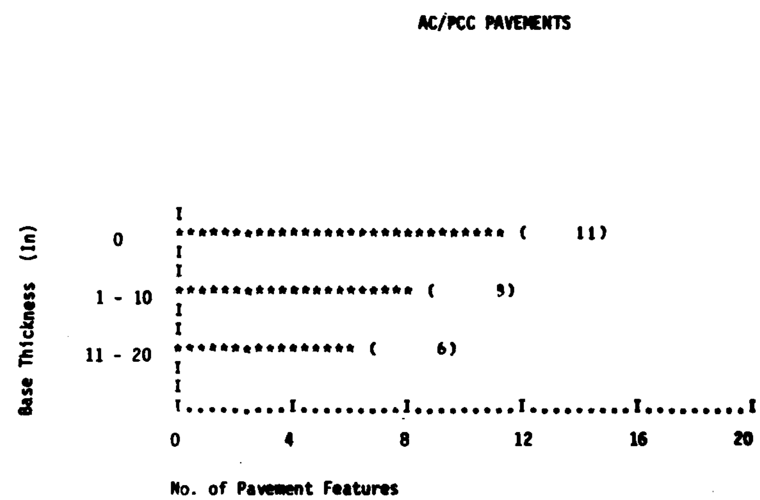

Figure 25. Histogram of AC/PCC Pavement Base Course Thickness in Inches.

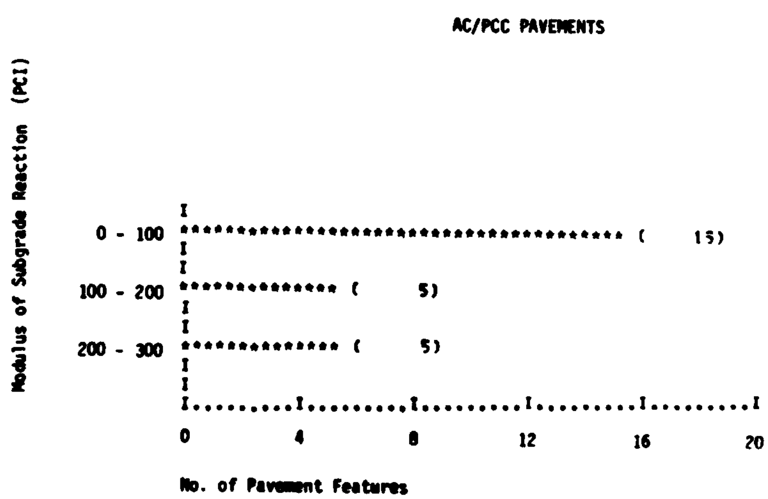

Figure 26. Histogram of AC/PCC Pavement Modulus of Subgrade Reaction in Pounds Per Cubic Inch.

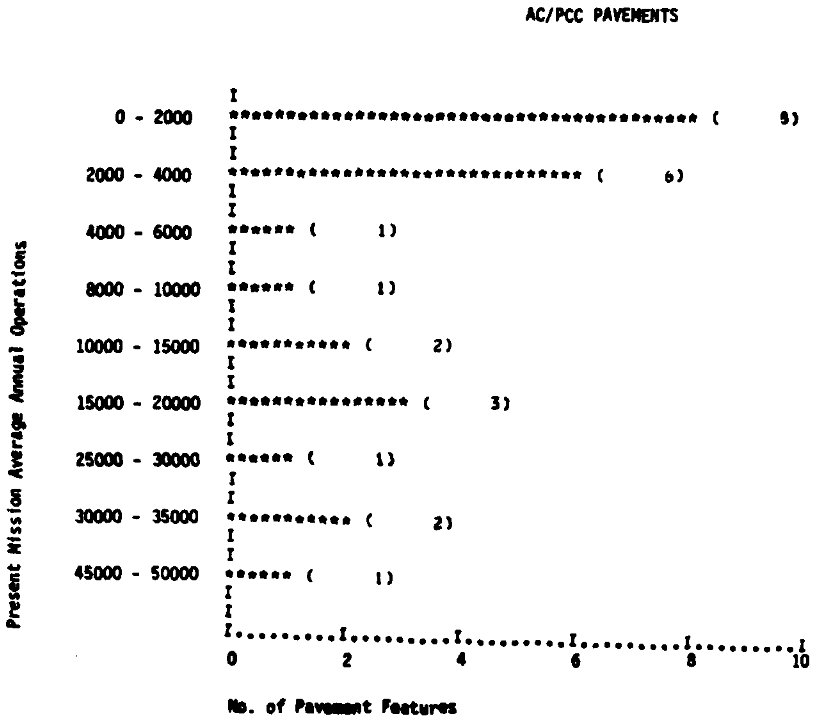

Figure 27. Histogram of Average Annual Volume of Traffic on AC/PCC Pavement.

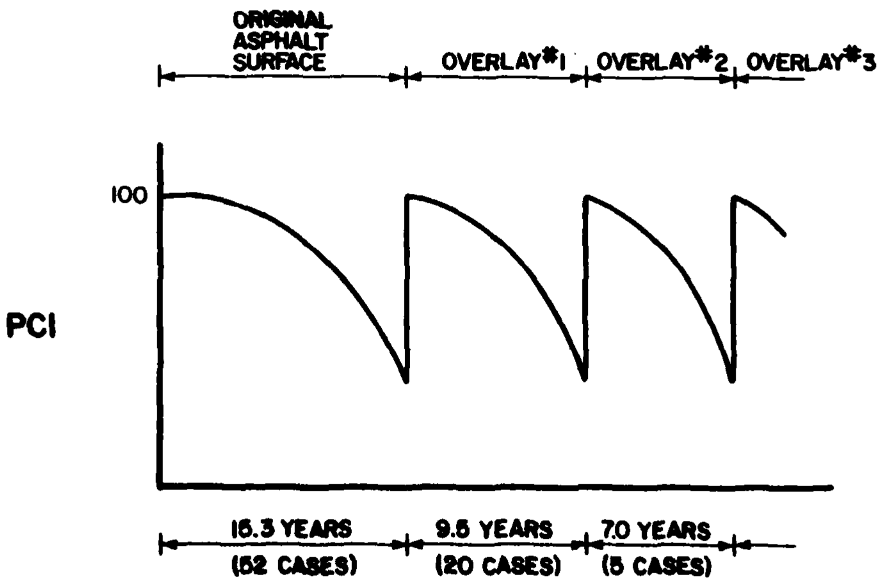

Figure 28. Average Age of an Asphalt Surface Before Overlay (Using FY 80 Data).

SECTION III

CONCRETE PAVEMENT PREDICTION MODELS

The main objective of a prediction model is to forecast the "consequences" of a variety of possible M&R strategies. Such a model would help greatly in deciding what M&R alternative to recommend for specific pavement features. Ideally, the model should be capable of forecasting the PCI for the following M&R strategies: if current local routine maintenance policies are continued; if major maintenance is applied; if overall M&R, such as overlay, recycling, or reconstruction is applied; and if a change in mission occurs. The model should also provide insight into variables that cause deterioration of concrete pavements and therefore could be used to predict the performance of new pavements for a variety of designs.

Two acceptable concrete prediction models were developed. The most extensive work was for developing a model to predict PCI for Portland Cement Concrete (PCC) and asphalt concrete overlay of PCC (AC/PCC). The initial model was developed in FY 79 with limited data. This model was improved by increasing the size of the data base, including both traffic data and asphalt-overlaid concrete pavements.

Extensive work was also done to develop prediction models for specific distress types. The two most promising models developed were (1) the corner break model, and (2) the cracking model.

All final prediction models presented in this report were developed in two distinct phases. The first phase was development of a linear regression model with as high an R^2 as possible. The second phase was use of the developed linear model as a starting point for nonlinear regression analysis (Reference 11). The SPSS statistical package was used in all development phases for all the models.

A. PCC AND AC/PCC PCI MODEL

A model was developed for predicting the PCI for both PCC pavements and PCC pavements overlaid with asphalt. Initially, a separate model for AC/PCC pavements was considered, but the limited number of cases (only 25) for this pavement type made this impractical. Using a transformed section analysis for stress determination (see Appendix B), the AC/PCC pavement features were combined with the PCC pavement features, and a PCI prediction model was developed to include both.

Data for developing the PCI prediction model were collected for 162 pavement features, 137 PCC pavements, and 25 PCC pavements overlaid with asphalt. Table 5 lists some of the pertinent statistical data.

Duplicated data were used in the PCI prediction models (i.e., the creation of new data points with the same characteristics, such as thickness, strength, etc., as the data collected in the FY80 survey). Since very few features in the data bank were new, the duplicated data consisted of cases where the age equaled zero and the PCI was set to 100. Thus, half the data population

TABLE 5. STATISTICS FOR PERTINENT PAVEMENT VARIABLES.

	Average Value	Standard Deviation	Low Value	High Value
NO OVERLAYS				
PCI	76.652	14.740	24	98
PCC THICK	15.625	3.858	6	24
AGE	17.978	7.353	2	37
MR	702.023	65.920	480	992
K-VALUE	239.606	116.162	15	500
PASSES/YR	17001.250	19804.793	0	75000
FATAGE	75716.871	120166.366	352	612654
DAMAGE	449.761	2773.442	0	26420
ONE AC OVERLAY				
PCI	66.520	16.187	17	87
PCC THICK	7.360	1.229	6	12
AC THICK	3.920	2.494	1.5	8
AGE	15.680	6.644	6	24
AGECOL	16.200	6.696	7	30
MR	554.167	237.860	450	900
K-VALUE	244.333	81.520	100	350
PASSES/YR	9780.000	12665.100	255	48150
FATAGE	151746.600	176564.628	3149	658325
DAMAGE	47880.252	77662.703	0	251360
DAMCOL	77998.633	160064.248	0	568460

Notes:

PCI: Pavement Condition Index

PCCTHICK: thickness, in inches, of the original PCC surface

ACTHICK: thickness, in inches, of the most recent AC overlay

AGE: age, in years, since original construction or, if overlaid, since the most recent overlay construction

AGECOL: age of the PCC slab, in years, at the time it is overlaid. If no overlay exists, AGECOL is zero.

MR: modulus of rupture, in pounds per square inch, of the PCC slab.

K-VALUE: modulus of subgrade reaction, in pounds per cubic inch. Reading is taken on the surface immediately below the PCC surface.

PASSES/YR: reported annual volume of traffic. This number represents the average number of passes per year the pavement services for the combined total of all aircraft types.

FATAGE: a mechanistic input variable used in the PCI prediction model. It represents the total critical stresses to which the pavement has been subjected.

DAMAGE: a mechanistic input variable used in the PCI prediction equation. Using a given procedure, determines the number of passes each aircraft can make over a given feature before structural damage occurs. The variable DAMAGE records how many times this number has been reached.

DAMCOL: same as DAMAGE, but records only the number before the pavement is overlaid.

i.e., DAMAGE = damage since overlay, or if no overlay, since original construction

DAMCOL = damage before overlay.

existed at one PCI value. It was felt that setting the PCI to 100 at age = 0 was a reasonable assumption.

For the first phase of model development, numerous stepwise regression analyses were performed using different variable combinations and interactions. Variables picked for regression analysis were selected using correlation matrices between variables and the PCI. Almost every conceivable form of variables considered as possible PCI predictors were tested. Scattergrams revealed ranges and general trends of the variables. Variables with the highest correlations were included in first runs. Partial correlations of other variables were then studied and the procedure continued. Results of each regression analysis were analyzed and new combinations and interactions of variables chosen. A sensitivity analysis was performed on the regression models that looked promising. (A full sensitivity analysis of the final model is presented under MODEL EVALUATION.)

The stepwise regression analysis procedure starts with the simple correlation matrix between the dependent variable (PCI) and each independent variable. It enters into regression the independent variables most highly correlated with the dependent variable (Step 1). Using partial correlation coefficients, it then selects the next variable to enter regression (i.e., the variable whose partial correlation with PCI is highest). At every step, the program reexamines the variables included in the equation in previous steps by testing each variable at each stage as if it has been the last to enter and by checking its contribution by means of the partial F-test.* Thus, some variables may be removed from the equation after they have been entered. After many attempts, the best linear regression model selected on combined statistical and engineering criteria was:

Phase 1 Model:**

$$
\begin{aligned}
PCI = 97.485 &- .23765 \times AGE \times LDAMAGE \\
&- .00053576 \times AGE^2 \times AAPREC \\
&- .0020311 \times AGE^2 \times FTC^{.5} \\
&- .000048516 \times AGE^2 \times FATAGE^{.5} \\
&- .11813 \left(\frac{AGE^{.5} \times AGECOL \times LDAMCOL}{THICK}\right)
\end{aligned}
$$

$R^2 = .66416$

Standard Deviation = 9.63233

The Phase 1 model is then used as a starting point for nonlinear regression analysis. For Phase 2, the functional form of the Phase 1 equation was input, using all coefficients and power functions as variables. The adjusted model from Phase 1 was represented as:

*Standard Statistical Test.
**Variable definitions begin on next page.

$$
\begin{aligned}
PCI = B(1) &- B(2) \times AGE^{B(3)} \times LDAMAGE^{B(4)} \\
&- B(5) \times AGE^{B(6)} \times AAPREC^{B(7)} \\
&- B(8) \times AGE^{B(9)} \times FTC^{B(10)} \\
&- B(11) \times AGE^{B(12)} \times FATAGE^{B(13)} \\
&- B(14) \left(\frac{AGE^{B(15)} \times AGECOL^{B(16)} \times LDAMCOL^{B(17)}}{THICK^{B(18)}} \right)
\end{aligned}
$$

The initial values of B(1) through B(18) were assigned so that the revised model was equal to the model from Phase 1. Limits were then placed on the values these variables could take. Using a method of partial derivatives, the nonlinear program chose values for the variables B(1) through B(18) to minimize the error in estimating the dependent variable (PCI). The results from early nonlinear regressions and the resulting trends of the values of variables B(1) through B(18) were analyzed and the influence of the individual variables (AGE, LDAMAGE, AAPREC, etc.) on the dependent variable (PCI) was evaluated. Sensitivity analyses were run to ensure that the model continued to meet various engineering criteria. After several nonlinear regression runs and analyses, the final model for PCI prediction was:

Phase 2 Model:

$$
\begin{aligned}
PCI = 99.536414 &- 2.6833 \times AGE^{.55857} \times LDAMAGE^{.6} \\
&- .0001757 \times AGE^{.5} \times FATAGE^{.74987} \\
&- .0021893 \times AGE^{1.0} \times AAPREC^{1.2188} \\
&- .02987057 \times AGE^{1.7366} \times FTC \\
&- .0319143 \left(\frac{AGE^{5} \times AGECOL^{.76544} \times LDAMCOL^{1.0}}{THICK^{1.6035}} \right)
\end{aligned}
$$

$R^2 = .74099$

$\sigma = 8.12136$

where:

PCI = Pavement Condition Index at the time of the survey.

AGE = time (years since original construction or, if overlaid, time since overlay construction)

AAPREC = average annual precipitation (inches)

FTC = discrete variable

= 1 if number of freeze-thaw cycles in a PCC pavement at a 2-inch depth is greater than or equal to 10.*

= 0 if the number of freeze-thaw cycles in a PCC pavement at a 2-inch depth is less than 10, or if the existing surface is an asphalt overlay.

*Freeze-thaw cycle information can be supplied by CERL or computed on a computer program provided by CERL.

THICK = the most recent overlay thickness (for overlaid pavements only).

AGECOL = age of previous surface layer before being overlaid. (Figure 29 graphically represents this variable.)

$$FATAGE = \sum_{i=1}^{a} (0.75)\ \sigma_{ei}/MR \times n_i \times AGE$$

a = number of different aircraft using the feature.

σ_{ei} = edge stress caused by aircraft i as computed by H51 (Reference 9) computer program (pounds/square inch).

MR = modulus of rupture of concrete (pounds/square inch).

n_i = total number of passes per year (not coverages) of aircraft i over pavement feature.

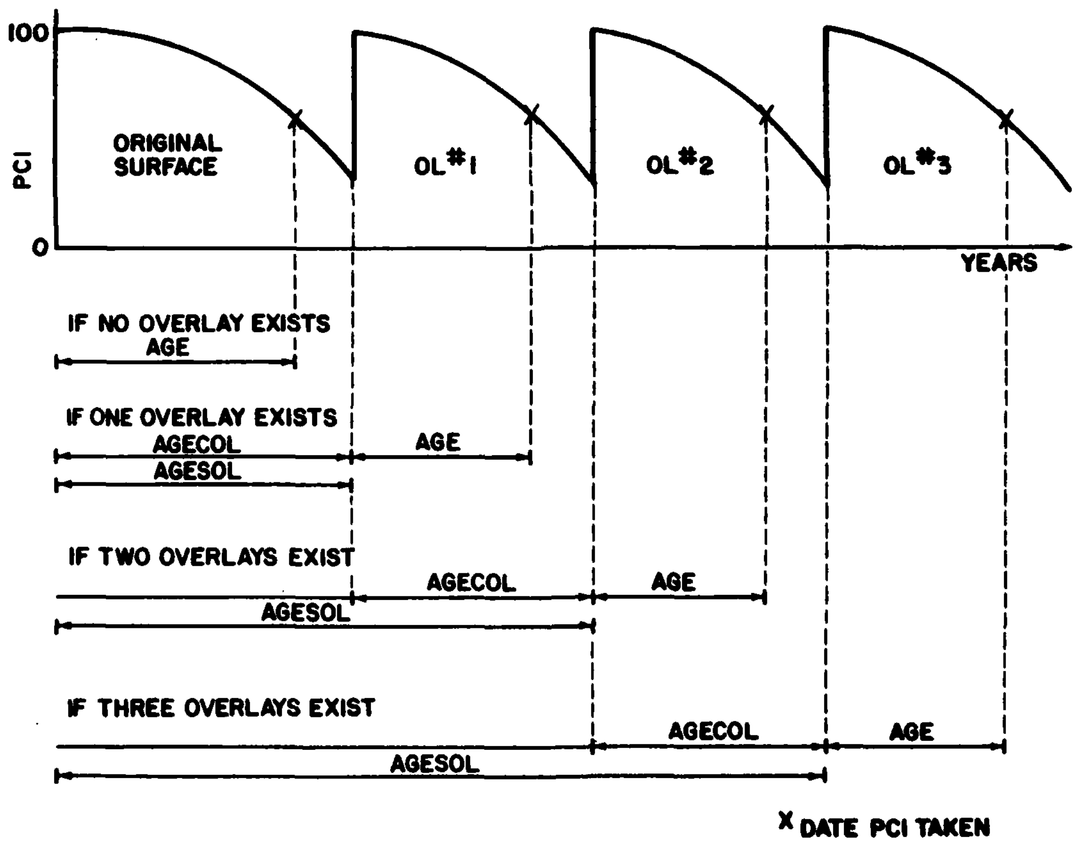

Figure 29. Illustration of Time-Period Variables.

LDAMAGE = Log_{10} (DAMAGE + 10)

DAMAGE = damage done to pavement since original construction or, if overlaid, since the most recent overlay.

$$= \sum_{i=1}^{a} \frac{n_i}{N_i} \times \text{AGE}$$

N_1 = number of repetitions of aircraft i to cause failure of concrete.

$$= 10^{(17.61 - .01761 \times \sigma_{ei})}$$

Note: If the edge stress $\leq$ 500, $\frac{n}{N}$ is assumed negligible.

If (17.61 - .01761 x σe) < 0, N is assumed to be equal to 1.

LDAMCOL = LOG(DAMCOL + 10)

DAMCOL = damage done to pavement structure during the time period "AGECOL." Calculated by the same procedure as "DAMAGE."

Two examples are provided to illustrate the calculation of the FATAGE and DAMAGE variables. The first example is a PCC pavement with no overlay. The second example is a PCC pavement with an early AC overlay.

Example 1: Calculation of FATAGE and DAMAGE for a PCC pavement with no overlay.

The given data for the pavement are:

PCC Thickness	14 inches
Modulus of Rupture	750 psi
Age of Pavement	8 years
K-Value	200 psi

Aircraft	Traffic Passes Per Year (n)
F4	15,000
C141	5,000
B52	50

Step 1: Calculate the edge stress each aircraft causes on the pavement structure. Using the graphs found in Appendix B, read the edge stress from the graph. When the reported K-value is not one of the graph contours, use linear interpolation to determine the edge stress for the given K-value. For this case, the edge stresses are:

Aircraft	Edge Stress
F4	380 psi
C141	665 psi
B52	1035 psi

Step 2: Compute FATAGE. Since FATAGE is a cumulative variable, it can be computed for each aircraft; then, summation for each aircraft will give the total FATAGE.

For one aircraft:

$$\text{FATAGE} = \frac{(.75) \times (\text{Edge Stress})}{\text{MR}} \times (\text{passes/year}) \times \text{AGE}$$

In this case:

$$\begin{aligned}
\text{F4} &= (.75)(\ 380)/750 \times (15{,}000)(8) = 45{,}600 \\
\text{C141} &= (.75)(\ 665)/750 \times (\ 5{,}000)(8) = 26{,}660 \\
\text{B52} &= (.75)(1035)/750 \times (\quad 50)(8) = \quad 414 \\
\text{FATAGE} &= \overline{72{,}614}
\end{aligned}$$

Step 3: Compute DAMAGE. The frst step is computing the allowable number of passes for each aircraft (N). After that, the damage caused by each aircraft can be calculated and the sum of the damages caused by each aircraft totaled.

Aircraft:

F4: Edge stress = 380 psi
Since the edge stress is less than 500 psi, the value $\frac{n}{N} = 0$.

(Note: $\text{DAMAGE} = \frac{n}{N} \times \text{AGE}$)

C141: Edge stress = 665 psi
$N = 10^{(17.61 - .01761 \times 665)}$
$= 793{,}140$

B52: Edge stress = 1035
$N = 10^{(17.61 - .01761 \times 1035)}$

(Note: $17.61 - .01761 \times 1035 \leq 0$; therefore, by definition, N = 1.)

For one aircraft:

$$\text{DAMAGE} = \frac{\text{Passes/year}}{\text{N}} \times \text{AGE}$$

In this case:

$$F4 = 0 = 0.0000$$

$$C141 = \frac{5{,}000}{793{,}140} \times 8 = 0.0504$$

$$B52 = \frac{50}{1} \times 8 = \underline{400.000}$$

$$DAMAGE = 400.0504$$

Example 2: Calculation of DAMAGE, FATAGE, and DAMCOL for an AC/PCC Pavement (one overlay).

Several factors about an overlaid pavement must be considered that are not considered in one that has not been overlaid. The given pavement data for this case are:

Aircraft	Passes Per Year
F4	15,000
C141	5,000
B52	50

Step 1: Determine edge stress for the 12-inch PCC pavement and for the 12-inch PCC pavement overlaid with 3 inches of AC. The edge stress for the 12-inch PCC section is taken from the graphs in Appendix B.

For the overlaid section, use the following procedure:*

1. Determine the edge stress if the entire section is PCC (in this case, 15 inches).

2. Compute the percentage of asphalt of the entire thickness (in this case, $\frac{3}{15} \times 100 = 20$).

3. Compute the multiplier:

   $$Y = 1.00 + 0.0143\ (\%\ ASPHALT)$$

   $$Y = 1.00 + 0.0143(20)$$

   $$= 1.286$$

4. Compute the edge stress for overlaid pavement:

*See Reference 12.

Edge Stress x Y = edge stress for overlaid pavement (for 15-inch PCC).

A table of edge stresses is:

Aircraft	Edge Stress for 12-inch PCC	Edge Stress for 15-inch PCC	Edge Stress for AC/PCC
F4	495	335	430
C141	800	615	790
B52	1320	930	1195

Step 2: Compute DAMCOL. To compute DAMCOL, use the same procedure as in Example 1. The stresses used for computing DAMCOL are those associated with the 12-inch pavement. The age used in computing DAMCOL is the age of the pavement before it was overlaid.

(1963 - 1943 = 20 years)

F4: Edge stress = 495 psi
$495 \leq 500$
Therefore, $\frac{n}{N}$ is negligible.

C141: Edge stress = 800 psi
$N = 10^{(17.61 - .01761 \times 800)}$
N = 3327.

B52: Edge stress = 1320 psi
$17.61 - .01761 \times 1320 \leq 0$
Therefore, by definition, N = 1.

DAMCOL Calculations:

$$F4 = 0.000$$

$$C141 = \left(\frac{5000}{3327}\right) \times 20 = 30.057$$

$$B52 = \left(\frac{50}{1}\right) \times 20 = \underline{1000.000}$$

$$DAMCOL = 1030.057$$

Step 3: Compute the variable DAMAGE, using the transformed section edge stresses. The pavement age used is 15 years (1978 - 1963).

F4: Edge stress = 430 psi
$430 \leq 500$
Therefore, $\frac{n}{N} = 0$.

C141: Edge stress = 790 psi
$N = 10^{(17.61 - .01761 \times 790)}$
= 4990.

B52: Edge stress = 1195 psi
$17.61 - .01761 \times 1195 \leq 0$
Therefore, by definition, N = 1.

DAMAGE Calculations:

$$F4 = 0 = 0.000$$

$$C141 = \left(\frac{5000}{4990}\right) \times 15 = 15.030$$

$$B52 = \left(\frac{50}{1}\right) \times 15 = \underline{750.000}$$

$$DAMAGE = 765.030$$

Step 4: Compute the variable FATAGE using the same edge stresses and age used in the damage calculations.

For a single aircraft:

$$FATAGE = \frac{(.75)(Edge\ Stress)}{MR} \times (Passes/Year)(AGE)$$

For this case:

F4	= (.75)(430)(15,000)(15)/750 =	96,750
C141	= (.75)(790)(5,000)(15)/750 =	59,250
B52	= (.75)(1195)(50)(15)/750 =	896
	FATAGE =	156,896

B. PCI MODEL EVALUATION

Figure 30 is a scattergram of predicted vs. actual PCI. The predicted values are plotted along the horizontal scale, and the actual values are plotted along the vertical scale. As the figure shows, the model is fairly good at predicting values above 65, but becomes less accurate at lower PCI values.

The model is evaluated further according to the following criteria:

1. Are the coefficients reasonable? All of the coefficients in the model are negative; this means that as any of the values of the variables increase, the PCI should decrease. This is reasonable in that all the variables are defined such that if they increase, the eventual pavement deterioration will also increase. The variables FATAGE, DAMAGE, and DAMCOL indicate the amount and type of traffic that the pavement has serviced. Thus, as either the total number of aircraft or the weights of the aircraft increase, these variables will increase. The environmental variables AAPREC and FTC are interacted with age, and record the effects of precipitation and freeze-thaw cycles on the pavement. Again, as the amount of precipitation or age increases, the pavement will deteriorate more, especially if it is also subjected to freeze-thaw cycles.

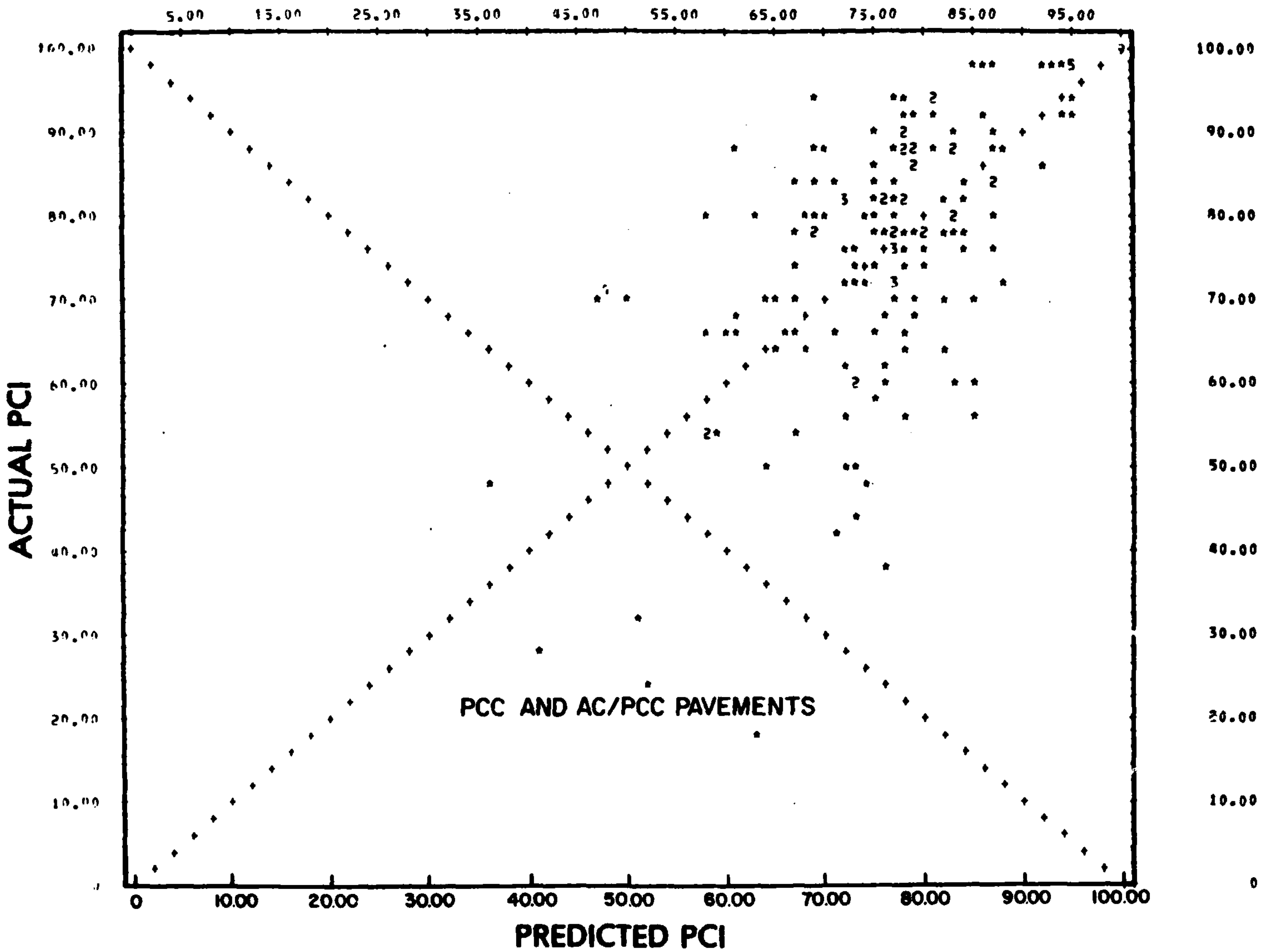

Figure 30. Scattergram of Actual PCI vs. Predicted PCI for PCC and AC/PCC Pavements Using Model Presented in Section III.

2. How sensitive is the model to factors affecting the PCI? The equation would represent a realistic situation if all the factors involved in pavement deterioration and its eventual PCI were included in the equation in their proper functional form. Many factors affect the PCI rating, including traffic, pavement structure, foundation, material properties, maintenance, and environment.

a. Traffic and Pavement Structure

The variables DAMAGE, FATAGE, and DAMCOL are directly influenced by traffic and pavement structure. First, these variables record amounts and types of traffic based on the edge stress caused by particular aircraft and the number of times the pavement is subjected to these stress levels. Pavement structure, particularly concrete thickness, is a major factor in determining the edge stress an aircraft causes in pavement. Figure 31 shows the effect of PCC thickness on the PCI. Figure 32 shows that within the design range for each aircraft, the PCC thickness has a major impact. When a certain thickness is reached, the PCI value levels off. Since all three aircraft approach the same value for upper and lower bounds, the PCI loss in thicker pavements can most likely be attributed to the effects of age and environment. Figure 33 shows the effects of the eventual overlay thickness for AC/PCC pavements on the PCI. Figure 34 shows the possible effects of increases in the number of passes for a given pavement structure and aircraft, and Figure 35 shows the effects of different traffic types on a pavement.

b. Foundation

The only input that relates to the foundation is the K-value (modulus of subgrade reaction) of the layer directly beneath the concrete slab. The K-value is a measure of the layer's relative stiffness and plays an important role in determining the edge stress caused by a given pavement-aircraft combination. In the ranges of concrete thickness where the PCI would vary if the concrete thickness were altered slightly, the K-value has a major impact. Figure 36 shows this effect. The pavement structure used in Figure 36 is well above that needed for the F-4 aircraft, and the K-value has little influence on the PCI. Using Figure 31, if values of PCC thickness were chosen that were not at the upper or lower limits for PCI values of the B-52 and F-4 aircraft, the K-value would also show a dramatic effect for these aircraft.

c. Material Properties

The material property that influences the model is the modulus of rupture (MR) of the concrete. A sensitivity analysis shows that for MRs ranging from 500 to 900 psi, the difference in PCI at an age of 25 years was only 5 points. This, plus the fact that there are no other variables relating to material properties and quality of construction, shows that the model is lacking in this area.

d. Maintenance

No variable in the model considers maintenance. The maintenance data collected were very ambiguous and often simply were not reported.

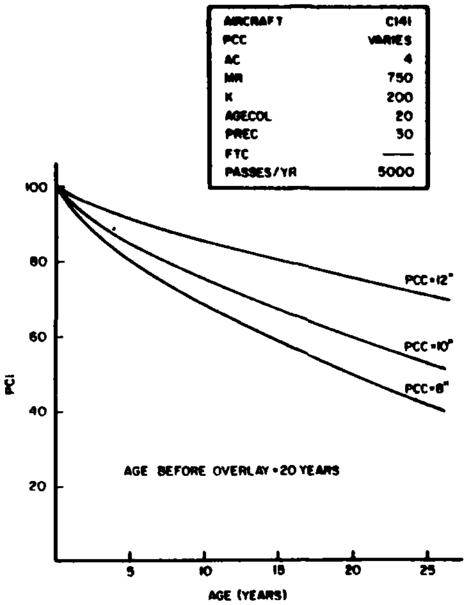

Figure 31. Effect of PCC Thickness on the PCI as a Function of Age.

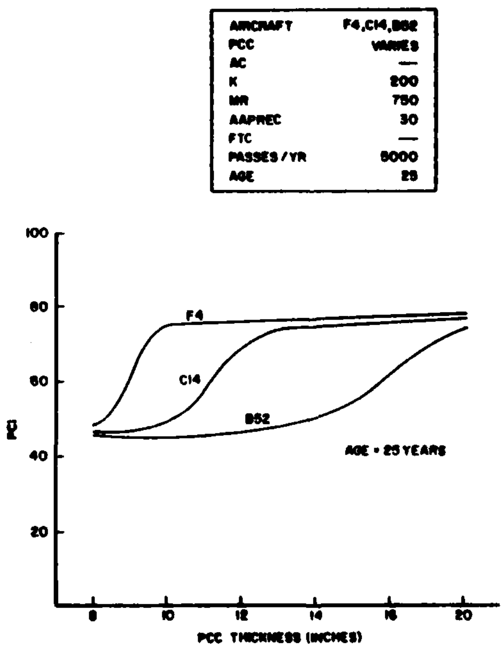

Figure 32. Effect of Aircraft Types on the PCI as a Function of PCC Thickness.

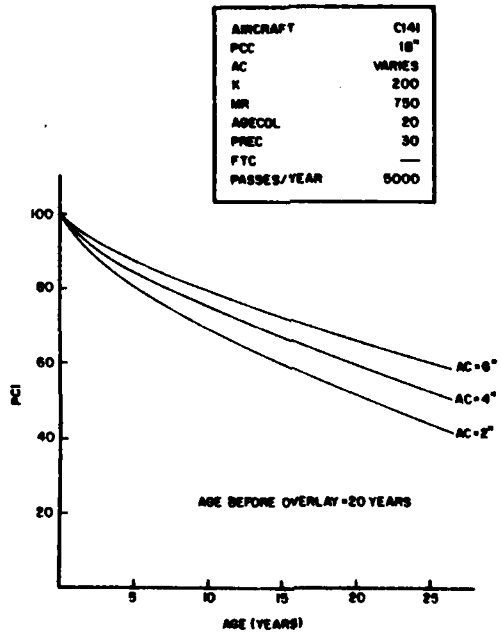

Figure 33. Effect of Asphalt Overlay Thickness on the PCI as a Function of Age.

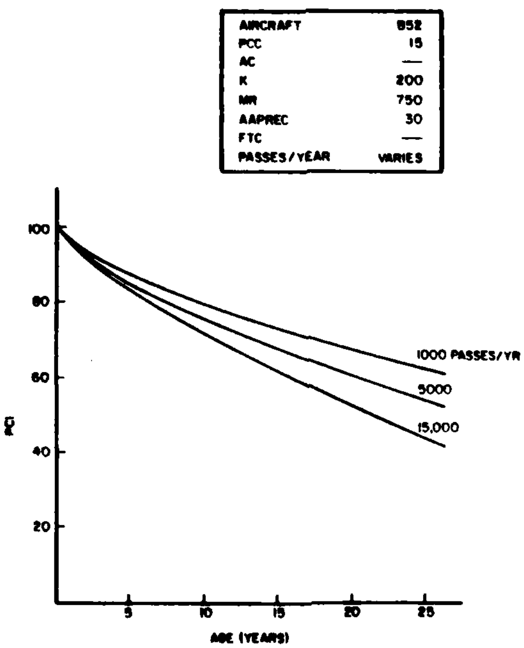

Figure 34. Effect of Traffic Volume (Passes) on the PCI as a Function of Age.

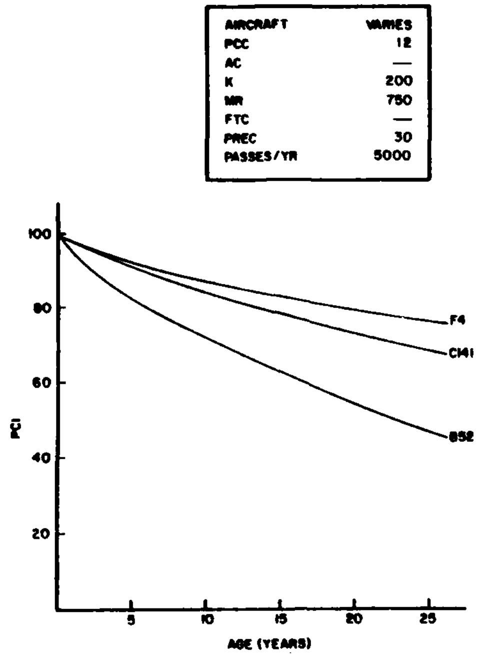

Figure 35. Effect of Aircraft Types on the PCI as a Function of Age.

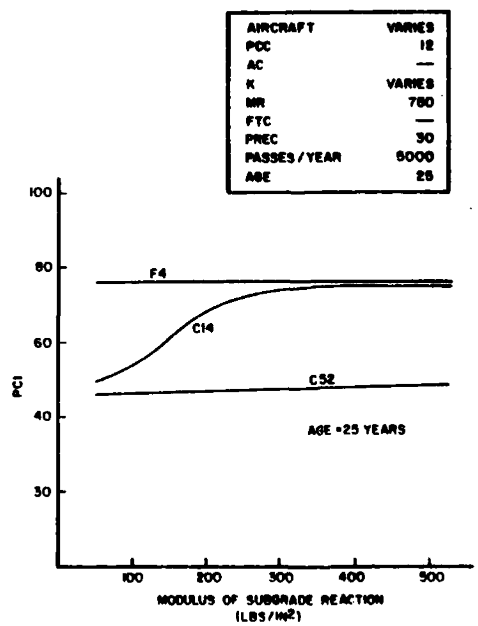

Figure 36. Effect of Aircraft Types on the PCI as a Function of Modulus of Subgrade Reaction.

Therefore, the model provides for only the average overall maintenance policy of the Air Force.

e. Environmental

The environmental variables are precipitation and the freeze-thaw cycle. Figure 37 shows the varying effects of these variables. The top three lines of the graph show the effects of varying amounts of rainfall with no freeze-thaw cycles. The bottom line shows the effect of freeze-thaw cycles at a rainfall of 50 inches per year. The difference between the two lower curves can be applied to the 10-inch and 30-inch rainfall curves to get predicted PCIs for freeze-thaw cycles for those rainfall values.

C. CORNER BREAK MODEL

A second model was developed to predict corner breaks for concrete pavements. The data for developing this model were collected from 137 non-overlaid PCC pavements. Table 6 lists some of the pertinent statistical data for these pavement features.

Duplicated data were not used in the corner break model because many features exhibited no distress (i.e., at age > 0, distress = 0). It was determined that by duplicating data for distress prediction, the models would not predict distresses adequately. Using duplicated data would have biased the data population to such an extent that the cases exhibiting distress would have had little effect on the model development.

As shown in Table 6, the actual amount of corner breaks is relatively low. (The amount of distress being predicted is the cumulative sum of all severity levels of the distress. For instance, if a pavement had 2.50 percent density of low-severity corner breaks and 3.00 percent density of medium-severity corner breaks, the amount the model would predict would be 5.50 percent.) Figure 38 shows a more detailed breakdown of the actual distress amounts.

The first step in developing the corner-break prediction model was to create and study several correlation matrices of possible predictor variables. Variables included in these early matrices covered the full range of collected data (see Tables 7 and 8). Table 7 is a list of essentially pure variables; that is, they have not been interacted with the age of the pavement. Table 8 contains the same variables, but these have been interacted with the age of the pavement.

Based on several correlation matrices, variables and variable combinations that appeared promising were studied further. Scattergrams were made to study trends of variables and to detect possible power functions of variables that could be made better predictors. Preliminary linear regression models were made and studied to find how variables would interact once they were actually in a prediction model. All early work pointed to a model heavily influenced by the mechanistic fatigue variables, and the age and thickness of the pavement. Attempts to create a model that included environmental variables were unsuccessful. The final linear regression model was:

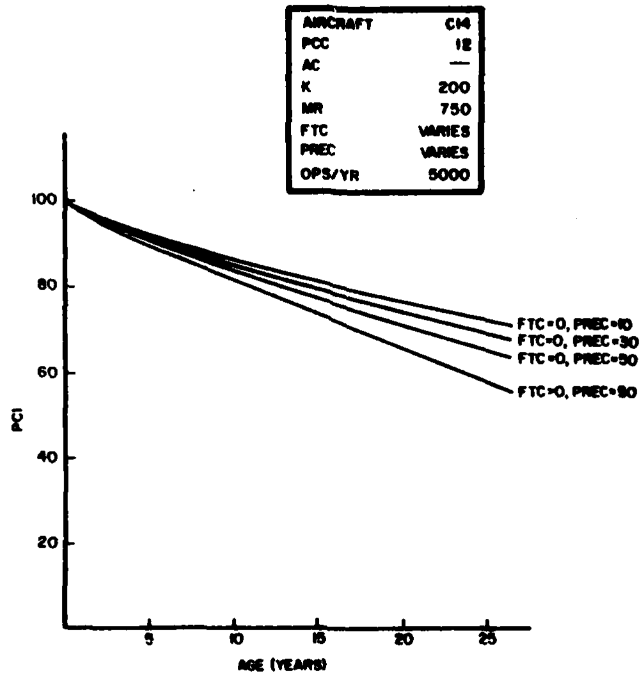

Figure 37. Effect of Rainfall and Freeze-Thaw Cycles on the PCI as a Function of Age.

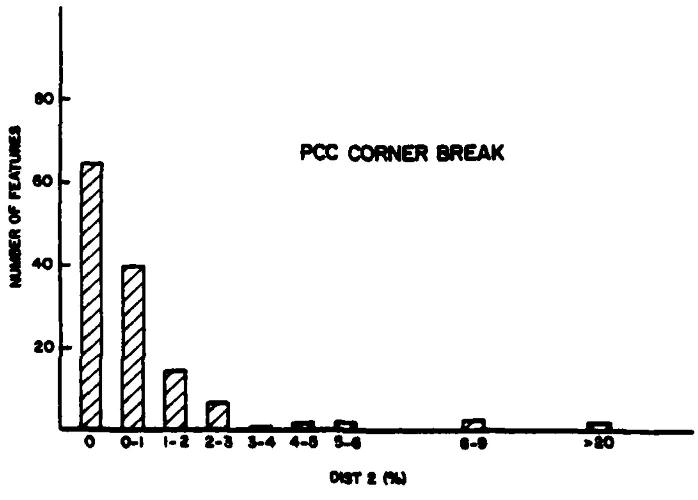

Figure 38. Histogram of the Percentage of Slabs Affected by Corner Breaks.

TABLE 6. STATISTICAL DATA FOR NONOVERLAID PCC PAVEMENTS.

	Average	Standard Deviation
Amount of Distress	1.202 (%)	3.595
Age of Pavement	17.978 (years)	7.285
PCC Thickness	15.625 (inches)	3.800

TABLE 7. VARIABLE DESCRIPTIONS FOR CORNER BREAK MODEL.

DIST2: the amount (in percent) of slabs that have corner breaks

AGE: the age since original construction of the pavement

FAT1: a cumulative fatigue variable that counts the linear amount of edge stress the pavement is subjected to

DAM1: a cumulative fatigue variable based on a predetermined allowable number of passes for each aircraft

LDAM1: the log (base 10) of the DAM1 variable plus 1.
$LDAM1 = LOG_{10} (DAM1+1)$

THICK1: the PCC thickness in inches

K1: modulus of subgrade reaction of the layer of material directly below the PCC (pounds per cubic inch)

MR1: modulus of rupture of the concrete slab

TEMP1: average annual temperature (^{o}F)

AATR1: average annual temperature range (^{o}F)

ADTR1: average daily temperature range (^{o}F)

PREC1: average annual precipitation (inches)

SR1: average annual solar radiation (Langleys)

JSR1: average July solar radiation (Langleys)

OPS1: cumulative passes per year of all aircraft over pavement feature

OPS2: OPS1 divided by THICK1

TABLE 8. CALCULATED VARIABLE DESCRIPTIONS FOR CORNER BREAK MODEL.

NFAT1:	AGE x FAT1	NAATR1:	AGE X AATR1
NDAM1:	AGE x DAM1	NADTR1:	AGE X ADTR1
NLDAM1:	AGE x LDAM1	NPREC1:	AGE X PREC1
NTHICK1:	AGE/THICK1	NSR1:	AGE X SR1
NK1:	AGE/K1	NJSR1:	AGE X JSR1
NMR1:	AGE/MR1	NOPS1:	AGE X OPS1
NTEMP1:	AGE x TEMP1	NOPS2:	AGE X OPS2

$$\begin{aligned} DIST2 = -.16569988 &+ .58483652E{-}03 \times I2LDAM2 \\ &+ .25816775E{-}07 \times I2FAT1 \\ &+ .12145016E{+}00 \times N2THK2 \end{aligned}$$

R^2 = .65709

σ = 2.13652 (standard error of estimate)

where:

DIST2 = amount of slabs having corner breaks (%)
I2LDAM2 = $AGE^2 \times LDAM^2$
AGE = age of pavement since original construction
LDAM* = LOG_{10} (DAM9+1)*

$$DAM^9 = \sum_{i=1}^{A} \frac{n_i}{N_i}$$

A = number of different aircraft using feature

n_i = actual number of applications of aircraft i over the life of the pavement

N_i = allowable applications of aircraft i based on the following criteria:

$$\log N_i = 17.61 - 17.61 \left(\frac{.75\ \sigma edge_i}{750}\right)$$

*See PCI prediction model for example calculation of LDAM.

$\sigma edge_i$ = edge stress created by aircraft i

Note: If $\sigma edge \leq 500$, N = 00

$\sigma edge \geq 2000$, N = 1

$$I2FAT1 = AGE^2 \times FATAGE$$

$$FATAGE^* = \sum_{i=1}^{A} \frac{.75\ \sigma edge_i}{MR} \times n_i$$

n_i = number of applications of aircraft i over life of the pavement

$\sigma edge_i$ = edge stress created by aircraft i

MR = modulus of rupture of the PCC slab

$$N2THK2 = AGE^2/THICK^2$$

THICK = PCC thickness (inches).

As with the PCI prediction model, this linear model was used as a starting point for nonlinear regression analysis. In nonlinear regression analysis, this model is represented as:

$$DIST2 = (1) + B(2) \times AGE^{B(3)}\ LDAM^{B(4)}$$
$$+ B(5) \times AGE^{B(6)} \times FATAGE^{B(7)}$$
$$+ B(8) \times AGE^{B(9)}/THICK^{B(10)}$$

Limits are put on the values the variables B(1) through B(10) may take. Then, using a method of partial derivatives, the computer picks values for the variables B(1) through B(10) that minimize the error in estimated DIST 2. The final prediction model for corner breaks is:

$$DIST2 = .22938517 + .29885368E-10 \times QFAT$$
$$+ .14236260E-00 \times QTHK$$
$$+ .13400729E-03 \times QDAM$$

$R^2 = .79687$

$\sigma = 1.64440$ (standard error of estimate)

where:

$$QFAT = AGE^{4.3905934} \times FATAGE^{.93912003}$$

$$QTHK = AGE^{3.5132394}/THICK^{4.5663156}$$

$$QDAM = AGE^{1.2932602} \times LDAM^{2.2705509}.$$

*See PCI prediction model for example calculation of FATAGE.

D. CORNER-BREAK MODEL EVALUATION

Figure 39 shows a scattergram which plots the predicted amounts on the horizontal scale and the actual amounts along the vertical scale. A glut of data points is found near or at the zero distress level. This diagram shows that the model predicts the higher distress amounts well (two points greater than 20 percent), but is less accurate at the lower distress levels. The model can be further evaluated according to the following criteria:

1. Are the coefficients reasonable? The signs of all the variables entered in the equation are positive, showing that as the value of any variable increases, the amount of corner breaks will also increase. This is reasonable, because the QFAT and QDAM variables are indicators of the amount and type of traffic the pavement has serviced. For a given pavement section, QFAT and QDAM will increase as the number of aircraft operations increases. Also, for a given amount of aircraft operations, as the equivalent single-wheel load again becomes greater, QFAT and QDAM will increase. The variable QTHK is independent of traffic. It considers only the PCC thickness and the age of the pavement. Its positive coefficient reflects that, as the pavement gets older, the amount of corner breaks will increase. Conversely, being an inverse function of pavement thickness, it predicts that, at a given age, a feature with thicker slabs will have fewer corner breaks than one with thinner slabs.

2. Is the equation plausible, i.e., how sensitive are the variables in the equation? The equation would be plausible if all the variables that affect corner breaks were included in the proper functional form. Many factors affect corner breaks, including traffic, slab dimensions, foundation, joint design, material properties, construction, and environment.

a. Traffic

The variables QFAT and QDAM are based on traffic and age. They are cumulative mechanistic variables that record amounts and types of traffic based on the edge stress created by different aircraft/pavement combinations. These variables represent the major portion of the predicted amount of corner breaks. Figures 40 and 41 show the varying influence that traffic type and amount have on corner breaks.

b. Slab Dimensions

Slab length and slab width were not used in this model because all slabs surveyed were 25 feet by 25 feet. Slab thickness is important in corner-break prediction, having a direct effect on the edge stress created by any type of loading. The edge stress is the major variable input into the QFAT and QDAM variables. Slab thickness is also considered in the QTHK variable. Figure 42 shows the influence of slab thickness on corner breaks.

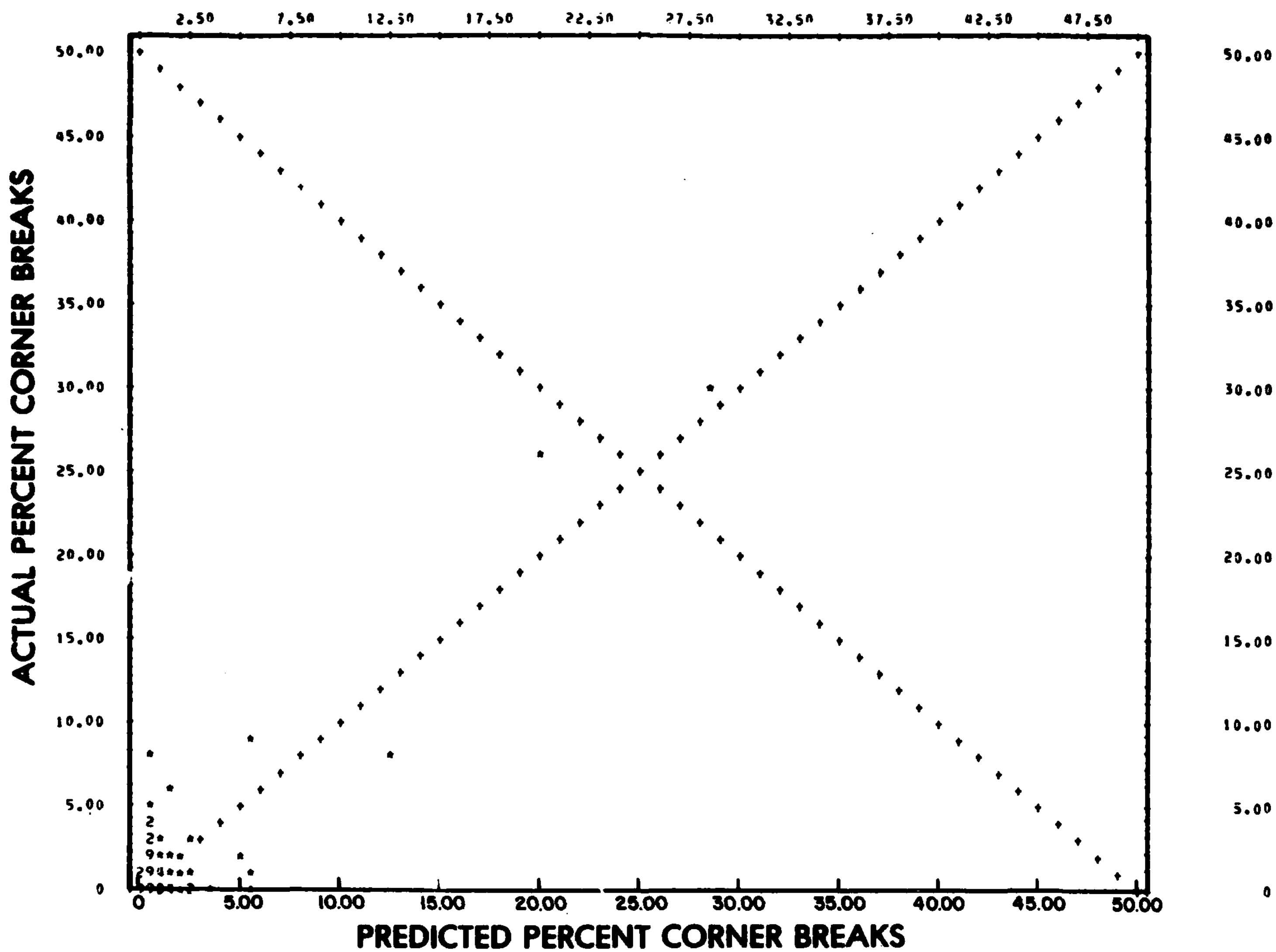

Figure 39. Scattergram of Actual Percent of Corner Breaking Observed vs. Predicted Percent of Corner Breaking Using Model Presented in Section III.

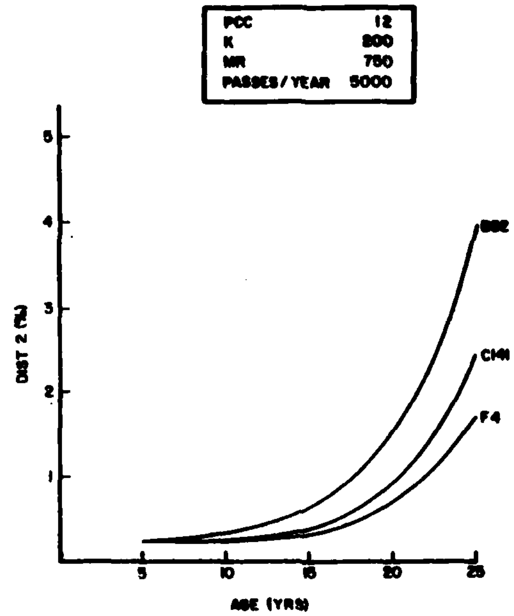

Figure 40. Effect of Aircraft Types on DIST2 (% Corner Breaks) as a Function of Age.

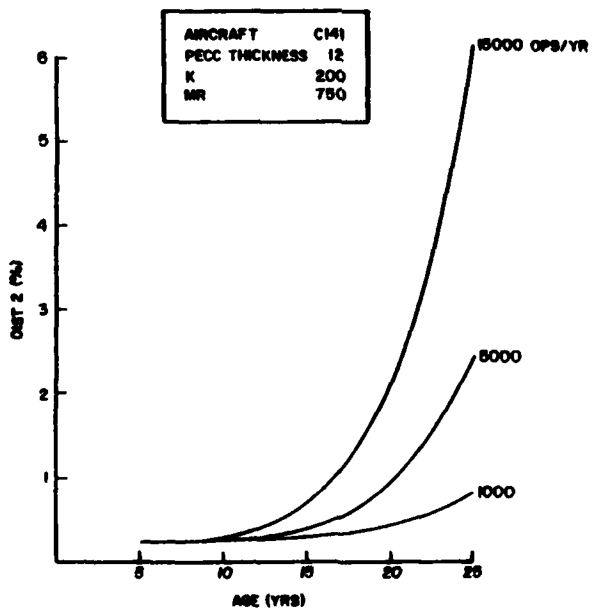

Figure 41. Effect of Traffic Volume on DIST2 (% Corner Breaks) as a Function of Age.

c. Foundation

The modulus of subgrade reaction (K-value) slightly influences the edge stress caused by a pavement-aircraft combination. Figure 43 shows the influence of this variable.

d. Joint Design

Joint design and performance should influence corner breaks. The important factor is how well the joints at the slab corner transfer and distribute the applied load. In the worst case, where no load is transferred to the surrounding slabs, the corner of the slab acts essentially as a cantilever. High tensile stresses develop in the concrete, and corner breaks begin to form. The range of data collected for joint design and performance proved to be insufficient for inclusion in the model.

e. Material Properties

The only material property represented in the model is the modulus of rupture of the concrete slab. Figure 44 shows the effects of differing MR values for a given pavement-aircraft combination.

f. Construction

There are no variables that consider construction.

g. Environment

There are no variables that consider environment. Early attempts to include environmental effects were unsuccessful, because the model always showed no environmental influence after the structure-type variables were included.

E. CRACKING-PREDICTION MODEL

A third model was attempted for predicting longitudinal, transverse, and diagonal (L, T, & D) cracking. Figure 45 shows a wide range and distribution of varying amounts of L, T, & D cracking. With this range and distribution, it was anticipated that a successful prediction model could be developed. However, poor correlation with many predictor variables was obtained, and the best equation developed had an R^2 of .33, which was considered unacceptable. Until the mechanism involved in the cause of cracking can be better represented numerically, cracking will remain difficult to predict.

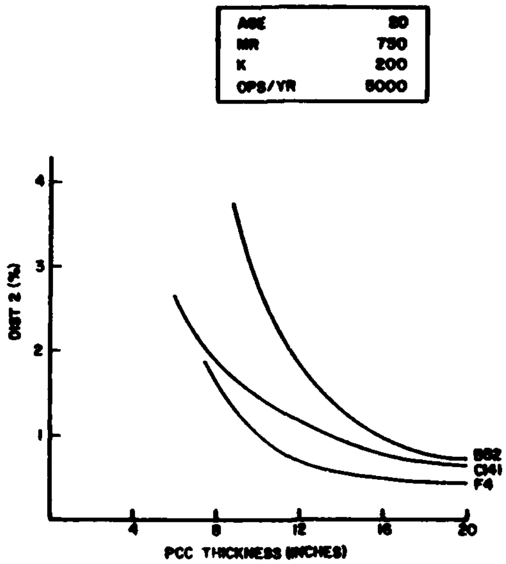

Figure 42. Effect of Aircraft Types on DIST2 (% Corner Breaks) as a Function of PCC Thickness.

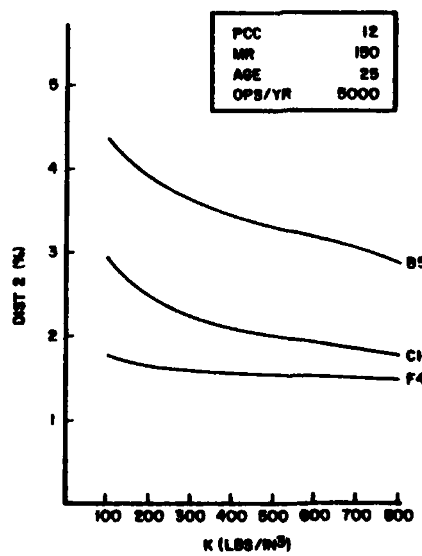

Figure 43. Effect of Aircraft Types on DIST2 (% Corner Breaks) as a Function of the Modulus of Subgrade Reaction.

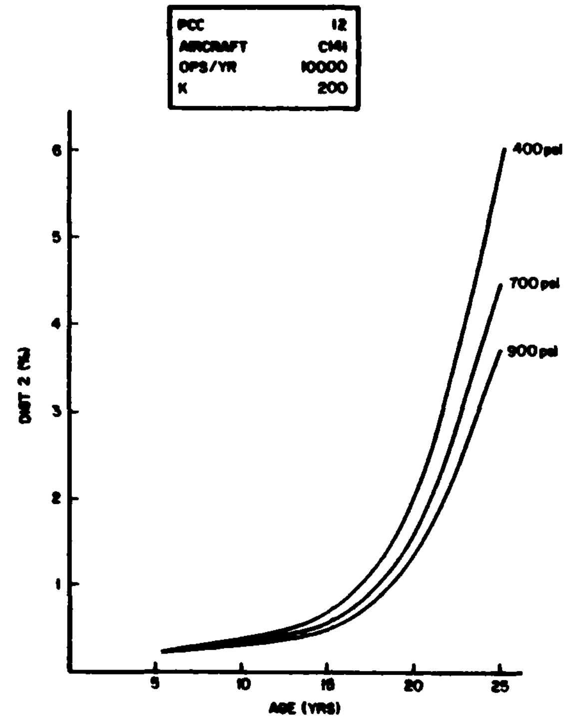

Figure 44. Effect of Concrete Modulus of Rupture on DIST2 (% Corner Breaks) as a Function of Age.

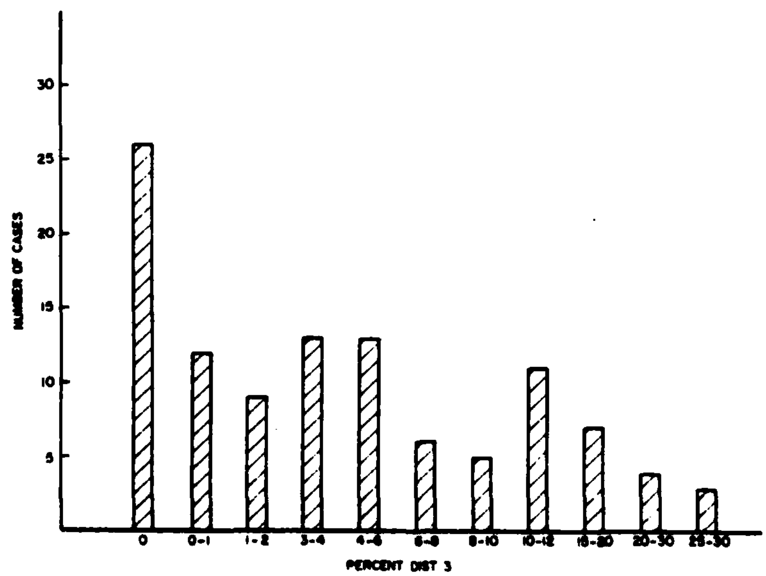

Figure 45. Histogram of the Percentage of Slabs Affected by Longitudinal, Transverse, and Diagonal Cracking.

SECTION IV

ASPHALT PAVEMENT PREDICTION MODELS

The objectives of asphalt pavement prediction models are similar to those of concrete models in that they should (1) be capable of forecasting the PCI for various M&R strategies, and (2) provide insight into the variables that cause pavement deterioration.

The data for the PCI prediction model for asphalt and asphalt-overlaid asphalt pavement were collected during FY 80 and checked with new data collected during FY 82. Models for predicting joint reflection cracking and alligator cracking were also attempted.

A. AC AND AC/AC PCI MODEL PRESENTATION

A model for predicting the PCI for asphalt (AC) and asphalt/asphalt (AC/AC) pavements was developed. Data were collected from 69 asphalt pavement features, 26 nonoverlaid pavements, and 43 features with one or more asphalt overlays. Table 9 provides statistical data on these features.

Duplicated data were used in the PCI prediction model. Duplicated data involves the creation of new data points with the same characteristics (e.g., thickness, strength, etc.) as the data collected in the FY 80 survey. Since very few features in the data bank were new, the duplicated data consisted of cases where the age equaled zero and the PCI was set to 100. Thus, half the data population existed at one PCI value. It was felt that setting the PCI to 100 at age = 0 was a reasonable assumption.

In developing the model, extensive use was made of the elastic layer theory computer program BISAR developed by Shell Oil Company. The program was used to determine the stress levels, strains, and deflections caused by particular aircraft/pavement combinations. These stress and deflection determinations were combined with knowledge of the total traffic amounts, and cumulative mechanistic variables were created. These variables record the amount of asphalt pavement fatigue based on the stress levels, strains, and deflections that different aircraft cause.

Early research revealed that the variable, AGE, was a very good predictor of PCI for asphalt pavements. Combinations of age with other variables, both environmental and mechanistic, were evaluated. Figure 46 shows a scattergram of PCI vs. AGE. When interacted with pavement age, almost every variable function became a possible PCI predictor. Several models were created and tested, and the following model was chosen:

$$PCI = 99.824036 - 9.214053 \times AGE^{.38719987} \times ADSUR^{.1} \times AVSUR^{.19120227}$$
$$- 1.0144967 \times 10^{-5} \times AGE^{1.7160520} \times VCOL^{.59024368}$$

$R^2 = .83389$

$\bar{\sigma} = 7.19736$ (standard error of estimate)

TABLE 9. STATISTICAL DATA FOR AC AND AC/AC FEATURES.

	Mean	Standard Deviation	Low	High
No Overlays (26 cases)				
PCI	67.308	17.756	31	100
SURTHICK	3.808	.708	2	5.5
PMAOPS	8371.808	14460.075	100	64200
AGE	17.077	8.727	0	27
SGCBR	13.269	8.151	6	35
BTHICK	7.135	3.719	6	24
1 Overlay (26 cases)				
PCI	72.615	12.989	39	100
SURTHICK	3.731	.962	2	7
OL1THICK	1.942	1.061	1	6
AGE	7.115	4.625	0	26
AGECOL	17.038	5.524	6	27
2 Overlays (12 cases)				
PCI	77.667	12.886	46	99
SURTHICK	4.167	1.642	2	7
OL1THICK	2.517	1.329	1	5
OL2THICK	1.833	.718	1.5	4
AGE	6.667	3.229	1	11
AGECOL	10.750	5.610	4	25
3 Overlays (5 cases)				
PCI	81.200	9.834	67	92
SURTHICK	3.200	1.643	2	5
OL1THICK	3.600	1.517	2	5
OL2THICK	1.660	.144	1.3	2
OL3THICK	1.900	.652	1.5	3
AGE	7.200	4.604	2	12
AGECOL	7.000	2.121	4	9

TABLE 9. STATISTICAL DATA FOR AC AND AC/AC FEATURES (CONCLUDED).

NOTES:

PCI:	Pavement Condition Index
SURTHICK:	thickness of original asphalt pavement in inches
PMAOPS:	present mission annual operations in passes per year
SGCBR:	subgrade California bearing ratio percent
BTHICK:	base thickness, in inches
OL1THICK:	thickness, in inches, of the first asphalt overlay
AGE:	age, in years, since original construction, or, if overlaid, since the most recent overlay construction (see Figure 29)
AGECOL:	age, in years, from the second most previous overlay, or construction date, to the most recent overlay. If no overlay exists, AGECOL=0 (see Figure 29)
OL2THICK:	thickness, in inches, of the second asphalt overlay
OL3THICK:	thickness, in inches, of the third asphalt overlay

where:

PCI = pavement condition index

AGE = age since original construction or, if overlaid, since overlay construction

ADSUR = function of the weighted average surface deflection divided by the equivalent single-wheel load.

$$= \frac{\sum_{i=1}^{x} \frac{n_i * T}{(P_i/\Delta_i) + 1}}{\sum_{i=1}^{x} n_i * T}$$

where:

n_i = number of passes per year that aircraft i makes over the pavement feature

x = number of different aircraft using pavement feature

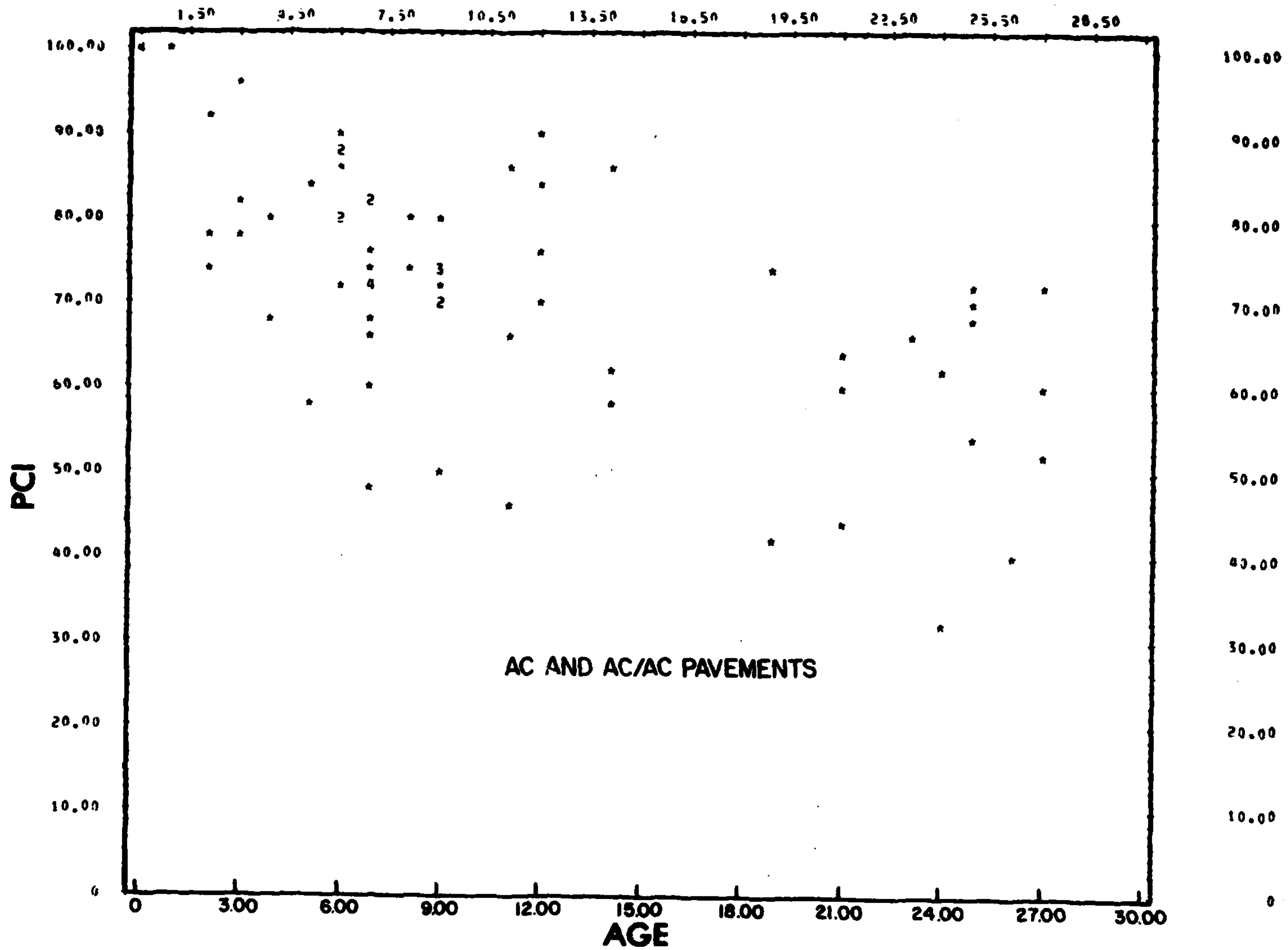

Figure 46. Scattergram of the Pavement Condition Index (PCI) vs. Age of Asphalt Surface (Years).

P_i = the equivalent single-wheel load for aircraft i. Table B-3 (Appendix B) provides a table of ESWL for various aircraft.

Δ_i = surface deflection under the wheel load of aircraft i. (Ccmputed by BISAR computer program.)

T = age of the existing pavement surface in years

AVSUR = weighted average vertical stress on the layer of material directly beneath the lowest asphalt layer

$$= \frac{\sum_{i=1}^{x} \sigma v_i * n_i * T}{\sum_{i=1}^{x} n_i * T}$$

where:

σv_i = vertical stress on top of the layer directly beneath the lowest asphalt layer (generally, the base course layer) caused by aircraft type i on the pavement cross section. (Value obtained from the BISAR computer program.)

n_i = number of passes per year made by aircraft type i over pavement feature

T = age of existing surface layer in years

VCOL = cumulative amount of vertical stress on top of the layer immediatly below the asphalt before pavement was overlaid. If not overlaid, VCOL = 0. Figure 47 shows "COL" variables and the time periods they represent.

$$= \sum_{i=1}^{x} \sigma v_i * n * AGECOL$$

where:

σv_i = vertical stress caused by aircraft type i on the top of the layer directly beneath the asphalt. In this case, the pavement cross section is the one before the overlay.

AGECOL = age of the asphalt surface before it was overlaid (see Figure 47).

The following example clarifies the calculations involved in predicting PCI.

Example 1: Calculation of predicted PCI for a 3-inch AC pavement with a 2-inch overlay.

The following information is given:

Date of original construction	1958
Initial asphalt thickness	3 inches
Initial granular thickness	12 inches
CBR of granular material	40
CBR of subgrade material	15
Overlay date	1973
Total asphalt thickness (initial plus overlay)	5 inches

Traffic information:

Aircraft	Passes/Year
T37	20,000
F4	5,000
C141	1,000

Environment information:

Assumed location is Mt. Home AFB

Average Annual Temperature	50.9°F
Average Annual Solar Radiation	393 Langleys

Step 1. Organize the given information into an easily readable form as shown in Figure 48.

Step 2. Compute VCOL. The first step in determining VCOL is determining the stiffness modulus for each layer to be used in the BISAR computer program. Appendix B outlines the procedure for determining this.

From Figure B-2:

- Half thickness of asphalt = 3/2 = 1.5
- Solar radiation = 395 Langleys
- Pavement temperature increase = 17.4°F
- $T_{PAVE} = T_{AIR} + T_{INCREASE}$

$$= 50.9 + 17.4$$
$$= 68.3^{\circ}F$$

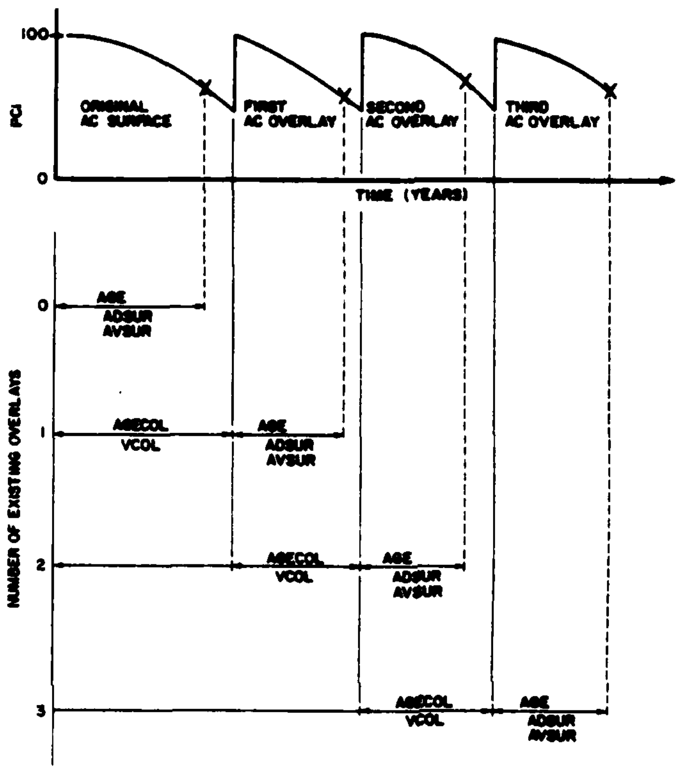

Figure 47. Illustration of Time Variables Associated with PCI Prediction Variables.

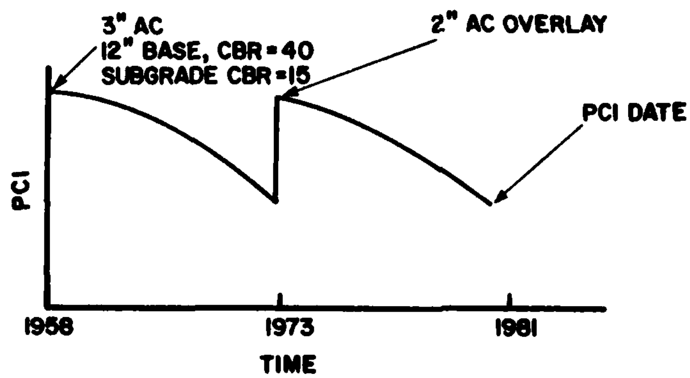

Figure 48. Illustration of Information Required for Example 1 in Section IV.

From Figure B-3:

$E_{AC} = 4.1 \times 10^5$ psi

For each aircraft, the granular base material can be characterized as a different stiffness based on the equivalent single-wheel load and tire pressure of the aircraft. Table B-3 lists many common aircraft, along with their ESWL and tire pressure. An A, B, C, or D classification is assigned to each aircraft. This classification determines which part of Figure B-4 to use in determining granular stiffness. For this case, the following values were used:

Aircraft	Aircraft Type	E Modulus
T37	A	64,000 psi
F4	D	76,000 psi
C141	D	76,000 psi

The subgrade E-modulus is taken as

$$1500 \times CBR = 1500 \times 10$$

$$= 15,000 \text{ psi}$$

These values of the E-modulus are used, along with the tire pressure and equivalent single-wheel load, as inputs into the BISAR computer program. The output from the program for this example was:

Aircraft	Vertical Stress on Base Course
T37	40 psi
F4	173 psi
C141	237 psi

Finally, VCOL is computed as follows:

VCOL: stresses x (Passes/Yr) x AGECOL

T37 = (40) X (20,000) X (15) = 12,000,000

F4 = (173) X (5,000) X (15) = 12,975,000

C141 = (237) X (1,000) X (15) = 3,555,000

ΣVCOL = 28,530,000

Step 3. Compute ADSUR. Again, the E-modulus for the different layers must be computed for 5 inches of asphalt. The procedure gives the following results:

Temperature Change	13°F
E_{AC}	500,000 psi
E_{GRAN} (T37)	54,500 psi*
(F4)	57,500 psi
(C141)	57,500 psi
$E_{SUBGRADE}$	15,000 psi

Output from the BISAR program is:

Aircraft	ESWL (Kips)	Surface Deflection
T37	3.8	.0062
F4	25.5	.0379
C141	58.97	.0834

Computation of ADSUR:

$$\text{ADSUR} = \frac{\text{DSUR}}{\text{ASUR}}$$

$$\text{ASUR} = \sum_{i=1}^{x} n_i \times \text{AGE}$$

$$\text{T37} = (20{,}000)(8) = 160{,}000$$

$$\text{F4} = (\ 5{,}000)(8) = 40{,}000$$

$$\text{C141} = (\ 1{,}000)(8) = \underline{8{,}000}$$

$$\text{ASUR} = 208{,}000$$

$$\text{DSUR} = \sum_{i=1}^{x} \frac{n_i * \text{AGE}}{(P/\Delta + 1)}$$

$$\text{T37} = \frac{(20{,}000)(8)}{(3.8/.0062) + 1} = 260.6274$$

$$\text{F4} = \frac{(5{,}000)(8)}{(25.5/.0379) + 1} = 59.3628$$

$$\text{C141} = \frac{(1{,}000)(8)}{(58.97/.0834) + 1} = 11.2982$$

*Using interpolation between graphs.

$$DSUR = 331.2885$$

$$ADSUR = \frac{331.2885}{208,000} = .001593$$

Step 4. Compute AVSUR. Output from the BISAR computer program gave the following stresses caused on top of the base course:

Aircraft	Stress
T37	20 psi
F4	97 psi
C141	153 psi

$$AVSUR = \frac{VSUR}{ASUR}$$

$$VSUR = \sum_{i=1}^{x} \text{(vertical stress)(passes per year)(age)}$$

$$T37 = (\ 20)(20,000)(8) = 3,200,000$$

$$F4 = (\ 97)(\ 5,000)(8) = 3,880,000$$

$$C141 = (153)(\ 1,000)(8) = \underline{1,224,000}$$

$$VSUR = 8,304,000$$

$$AVSUR = \frac{8,304,000}{208,000} = 39.92$$

Step 5. PCI prediction.

$$PCI = 99.82 - (9.214) \times (8^{.3872}) \text{ s } (.001593^{.1}) \times (39.92^{.1912}) -$$

$$(1.0145E\text{-}05) \times (8^{1.716}) \times (28,530,000^{.5902})$$

$$PCI = 99.82 - 21.90 - 9.04$$

$$= 68.88$$

B. PCI MODEL EVALUATION

Figure 49 is a scattergram of the predicted PCI vs. the actual PCI. This figure is the best argument for the validity of the model. Above the value of

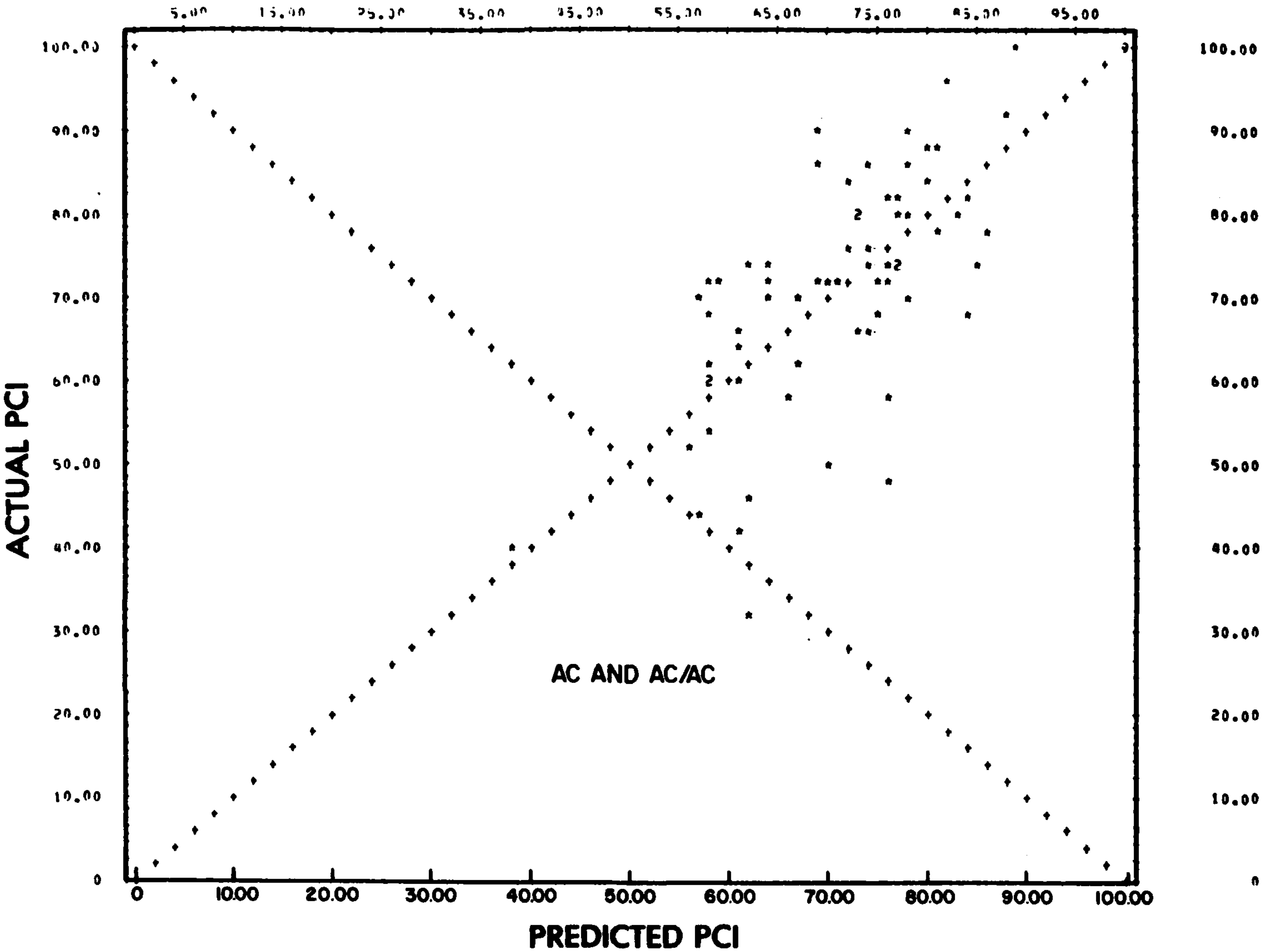

Figure 49. Scattergram of Actual PCI vs. Predicted PCI for AC and AC/AC Pavements Using Model Presented in Section IV.

about 50, the model does remarkably well in predicting PCI. Below 50, the model tends to predict PCIs a little higher than they actually are, but overall, the figure is very encouraging.

The model is further evaluated as follows:

1. Are the coefficients reasonable? The coefficients in this model are all negative. Pavement condition is a function of age. This is particularly true in asphalt pavement as the collected data and this model both show. The first variable computes a weighted average of the type of traffic that the pavement has serviced and interacts this value with the pavement age. The second variable mechanistically keeps track of how much traffic the pavement has serviced before overlay. It then interacts this amount of traffic with the age of the overlay. Increases in age, age before overlay, traffic before overlay, or average size of traffic should cause a lower PCI, and the model reflects this.

2. Is the equation plausible? How sensitive is the model to factors affecting the PCI? A truly realistic model would result if all the variables that affect the PCI of asphalt pavements were included in their proper functional form. Some of the variables that affect asphalt pavements are traffic, pavement structure, maintenance, foundation, condition before overlay and environment.

a. Traffic

The actual amount of traffic is not used in the model. An average of all traffic is recorded in the variables AVSUR (average vertical stress on the base course) and ADSUR (average deflection caused by an average equivalent single-wheel load). These variables are interacted with age. Figure 50 shows how type of traffic affects PCI. The actual number of passes per year has no influence other than how it affects the average vertical stress.

b. Pavement Structure and Foundation

Pavement structure affects PCI in that it directly influences the stresses and deflections caused by different aircraft. Figure 51 shows some of the influence asphalt thickness has on the PCI. The figure does not use any data for damage before overlay because it is assumed that the pavements were originally built with these asphalt thicknesses. However, it should be noted that when overlay effects are included, the differences become more pronounced because the overlay variable counts actual numbers, while the surface variables simulate average aircraft interacted with age.

Of all the inputs into pavement structure, asphalt thickness and asphalt stiffness proved to be the most influential. The model is considered deficient for other inputs such as subgrade CBR and base thickness. Figure 52 shows the influence of CBR on a nonoverlaid pavement; sensitivity for base thickness also shows the same type of results.

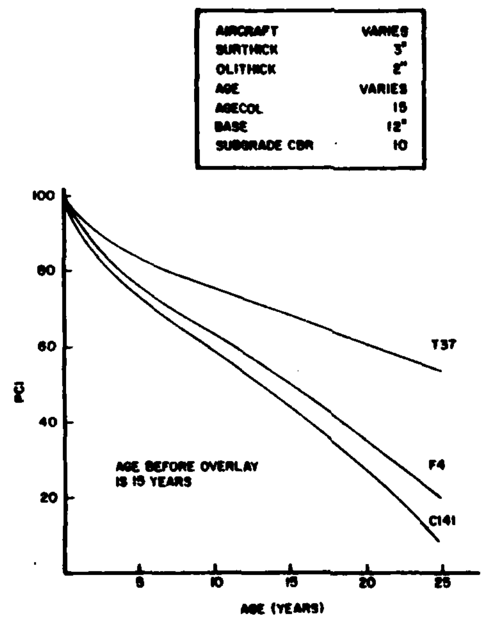

Figure 50. Effect of Aircraft Types on the PCI as a Function of Age.

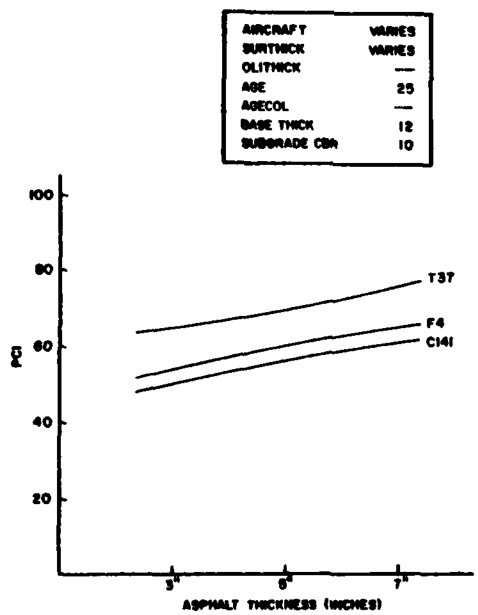

Figure 51. Effect of Aircraft Types on the PCI as a Function of Asphalt Thickness.

c. Maintenance and Condition Before Overlay

As with all pavements, maintenance plays an important role in determining PCI. Data gathered for this area included how often major maintenance projects were scheduled and the overall maintenance policy for cracks. However, missing information caused these variables to be unusable for the prediction models.

Condition before overlay is tied in with how well the overlay performs. There were no definite data on the actual condition of the pavement features at time of overlay, but information was available regarding how much traffic each pavement had serviced and the stress levels this traffic caused. The variable VCOL accounts for this traffic and indicates the pavement's condition at time of overlay. Figure 53 shows the effect of waiting different time periods before overlaying when all else remains the same. Figure 54 shows the same time period before overlay, but with different absolute amounts of traffic.

d. Environment

The environment affects pavement in terms of average daily temperature and solar radiation. Both of these factors are inputs for determining the E-modulus for asphalt. The model contains no direct environmental variables.

C. JOINT REFLECTION CRACKING

Data for developing a prediction model for joint reflection cracking were collected from 25 PCC pavements overlaid with one or more asphalt layers. Table 10 gives some of the pertinent statistical data for those pavement features.

TABLE 10. STATISTICAL DATA FOR CONCRETE PAVEMENTS WITH ASPHALT OVERLAYS

	Number of cases	$\bar{x}$	σ	Min	Max
PCC Thickness	25	7.36	1.229	6.	12.
1st Overlay Thickness	25	3.92	2.49	1.5	8.0
2nd Overlay Thickness	6	1.45	.122	1.2	1.5
3rd Overlay Thickness	2	8.00	0.	8.0	8.0
Age Before 1st Overlay	25	16.2	6.70	7.	30.
DIST 7	25	7.84	4.53	0.	15.86
Age	25	15.7	6.64	6.	24.

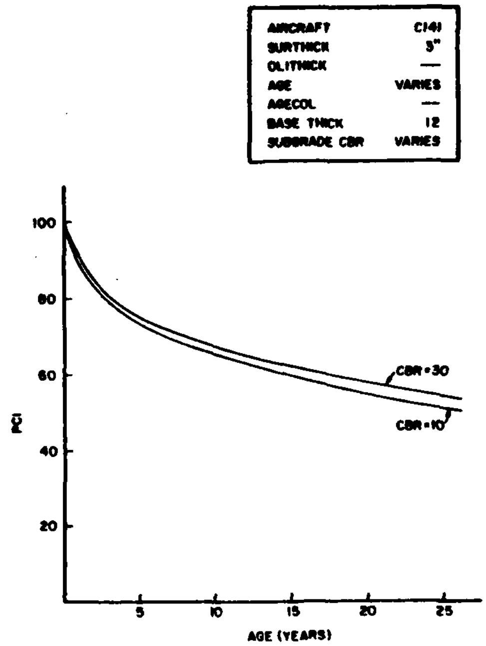

Figure 52. Effect of Subgrade CBR on the PCI as a Function of Age.

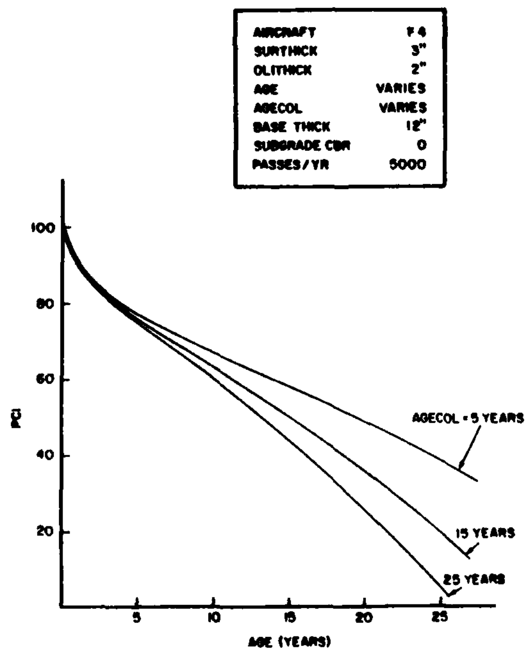

Figure 53. Effect of AGECOL on the PCI as a Function of Age.

The average value for DIST 7 (joint reflection cracking - 7.8 percent) was significantly higher than the amount of other distress types. There was only one reported case where the amount of distress was zero. Figure 55 gives a numerical breakdown of the amounts of DIST 7 reported. The figure shows that the breakdown of reported amounts is well distributed over a wide range of values. Duplicated data were not used in developing this model, since it was not felt that DIST 7 necessarily equaled zero at AGE = 0.

Early studies of the data revealed that the variable FATAGE was a very good predictor of the amount of DIST 7. All the steps taken to develop other prediction models were followed to ensure coverage of all variables as possible predictors. Scattergrams, correlation matrices, and regression runs were used to study an assortment of variables and variable combinations. The variable FATAGE remained the best predictor available.

When a decision was reached to definitely include the variable FATAGE, the next step was to find another variable that would improve the model and work well with it. The variable showing the best influence was the environmental variable of average daily temperature range. Interacting the average daily temperature range with the age of the pavement and then combining it with FATAGE in a prediction gave the best results. The linear regression model for DIST 7 prediction is:

$$\text{DIST 7} = -.9520015 + .014001348 \times \text{IFAT} + .002204033 \times \text{IADTR}$$

$$R^2 = .73863$$
$$\sigma = 2.41791 \text{ (standard error of estimate)}$$

where:

DIST 7 = amount of pavement having joint reflection cracking present (%)

$\text{IADTR} = \text{AGE}^{.5} \times \text{ADTR}^2$

AGE = age in years since most recent overlay

ADTR = average daily temperature range (^{o}F)

$\text{IFAT} = \text{FATAGE}^{.5}$

$$\text{FATAGE} = \sum_{i=1}^{x} \frac{.75\sigma_e \, ci}{MR} * n_i * \text{Age}$$

i = Counter for ith aircraft

x = number of different aircraft types using the pavement

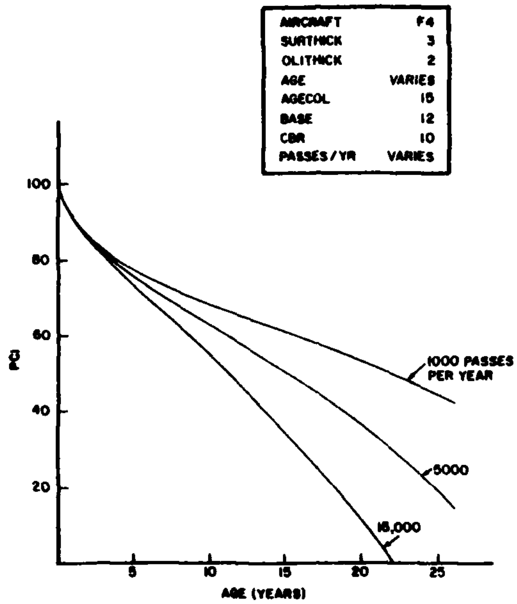

Figure 54. Effect of Traffic Volume on the PCI as a Function of Age.

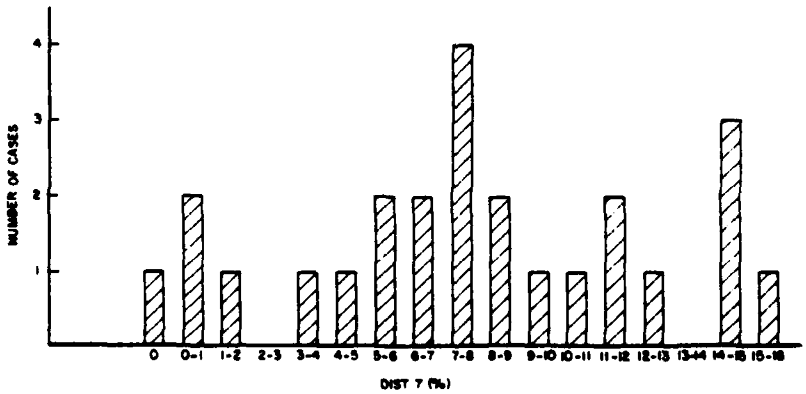

Figure 55. Histogram of the Percentage of Slabs Affected by Joint Reflection Cracking.

MR = modulus of rupture of the concrete slab beneath the asphalt (pounds/square inch)

n_i = number of passes per year of aircraft (i) over the pavement feature.

$\sigma_e(i)$ = edge stress at the bottom of the concrete slab caused by aircraft (i)

With PCC pavements overlaid with asphalt, the procedure for calculating the edge stress, and hence, the variable FATAGE, is somewhat involved. The following example for predicting the amount of joint reflection cracking helps clarify the procedure.

Example:

Average daily temperature range	$25^{o}F$
PCC thickness	10 inches
Asphalt thickness*	4 inches
Modulus of rupture of PCC	750 pounds/square inch
Modulus of subgrade reaction (K)	200 pounds/cubic inch
Age since last overlay	15 years

TRAFFIC INFORMATION

Aicraft	Passes per Year
F4	8000
C141	4000

1. The first step is to determine the edge stress that each aircraft would cause in a slab that has a PCC thickness equal to the PCC thickness plus the asphalt thickness (in this case, 14 inches**,***).

Aircraft	Stress
F4	380 psi
C141	670 psi

2. The next step is to calculate a multiplication factor based on the percent of asphalt in the layer.

$$\text{Asphalt Percentage} = \frac{4}{14} \times 100 = 28.57$$

*Asphalt thickness refers to the total amount of asphalt. This includes all overlays.

**Stress charts are used for this determination (see Appendix B).

***A more complete discussion of the transformed section procedure is presented in Reference 7.

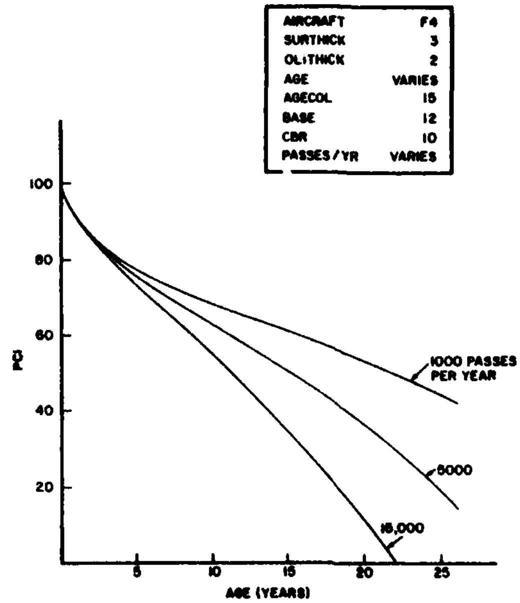

Figure 54. Effect of Traffic Volume on the PCI as a Function of Age.

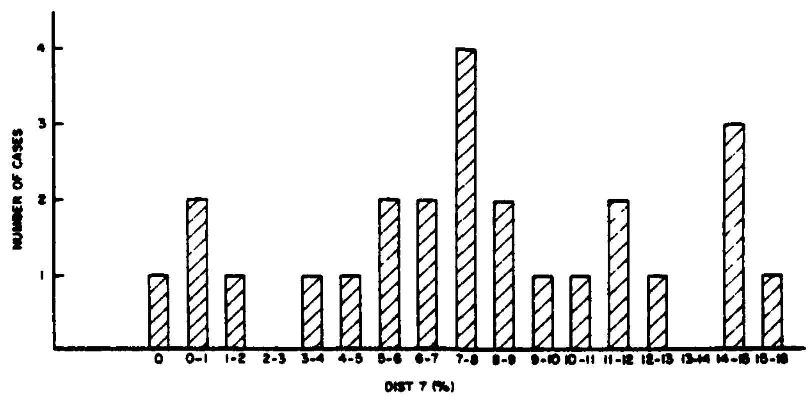

Figure 55. Histogram of the Percentage of Slabs Affected by Joint Reflection Cracking.

Multiplication Factor Y = 1.00 + (.0143)(28.57)

= 1.4086

Actual edge stress:

	σ_{14}		Y		σ_e
F4	380	x	1.4086	=	535
C141	670	x	1.4086	=	945

3. The final step for FATAGE calculations is to sum the total effect of the aircraft.

Aircraft	.75 σ_e		Passes/Year		Age		FATAGE
F4	(.75)(535)/750	x	8000	x	15	=	64,200
C141	(.75)(945)/750	x	4000	x	15	=	56,700
						TOTAL =	120,900

$FATAGE^{.5} = 347$

4. The variable IADTR is straightforward and calculated as follows:

$$
\begin{aligned}
IADTR &= AGE^{.5} \times ADTR^2 \\
&= 15^{.5} \times 25^2 \\
&= 2421
\end{aligned}
$$

5. The final step is to input the variable values into the prediction equation.

$$
\begin{aligned}
DIST\ 7 = -.95200115 &+ (.014001348 \times 347) \\
&+ (.002204033 \times 2421)
\end{aligned}
$$

$$= 9.24 \text{ percent}$$

The linear regression model for joint reflection cracking was used as a starting point for nonlinear regression analysis. However, prediction models resulting from nonlinear regressions showed little, if any, improvement over the linear model in predicting joint reflection cracking. Also, sensitivity to the input variables became less favorable with the nonlinear models. Therefore, the linear model was selected as the final prediction model for joint reflection cracking.

D. JOINT REFLECTION CRACKING MODEL EVALUATION

Figure 56 is a scattergram of the predicted versus the actual amounts of DIST 7. As shown, the model does a good overall job in predicting the amount

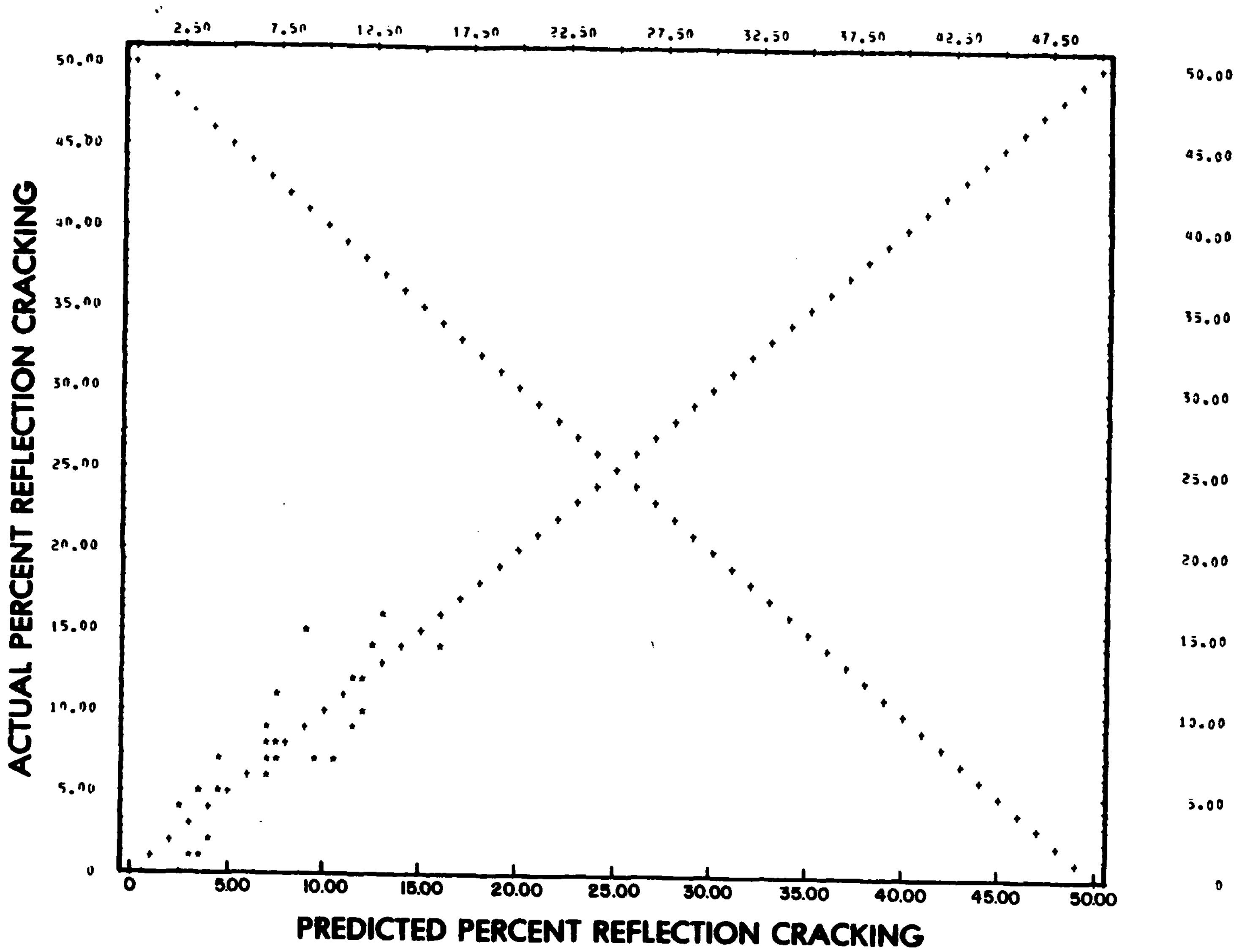

Figure 56. Scattergram of the Actual Percent of Joint Reflection Cracking vs. the Predicted Percent of Joint Reflection Cracking.

of DIST 7. The predicted levels are shown along the vertical axis. Overall, the model is simple to use.

The model can be further evaluated as follows:

1. Are the coefficients reasonable? The signs of both variables in the equation are positive. This is reasonable because as the value of FATAGE increases, the amount of cracking should also increase. The variables that affect FATAGE are type of aircraft, number of passes of the aircraft, and overall pavement thickness. FATAGE will increase as aircraft get heavier and the number of passes increases. Thickness works as an inverse to edge stress. Thicker pavements experience a lower edge stress for a given aircraft loading than thinner pavements. The lower stresses show up as lower values of FATAGE and therefore exhibit less cracking. The variable for average daily temperature range represents the amount of thermal gradients to which the pavement is subjected. As the age of the pavement or the daily temperature range increases, so will the amount of gradients that a pavement will experience. Increases in this number should be reflected in higher amounts of cracking, as shown by the positive coefficient in front of the daily temperature range variable.

2. Is the equation plausible, i.e., how sensitive is the model to factors affecting joint reflection cracking? The equation would be plausible if all the variables that affect joint reflection cracking were included in the proper functional form. Factors that affect joint reflection cracking include traffic, pavement thickness, environment, previous maintenance, and age before the overlay.

a. Traffic

The variable FATAGE is a cumulative mechanistic variable that records types and amounts of traffic based on the edge stress created by different pavement/aircraft combinations. This variable accounts for about half of the amount of distress predicted. Figures 57 and 58 show the effect of traffic on the amount of cracking. Figure 57 shows the effect of differing aircraft, which is significant, but Figure 58 seems to suggest that the number of passes has a larger influence. This might indicate that the number of times the asphalt is loaded over a joint is more influential than just an increase in load.

b. Pavement Thickness

In particular, asphalt overlay thickness would be expected to influence the amount of joint reflection cracking observed. Several attempts were made to try to include this variable in a more positive manner, but none succeeded. Figure 59 shows that the influence of overlay thickness is minimal, possibly because the average PCC thickness used to develop this model for these pavements is less than 8 inches; thus, even with overlay, the pavements may be severely overloaded.

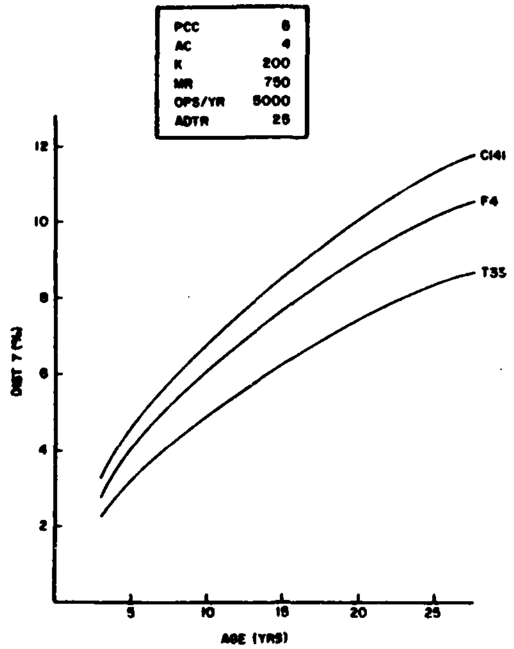

Figure 57. Effect of Aircraft Types on DIST7 (% Joint Reflection Cracking) as a Function of Age.

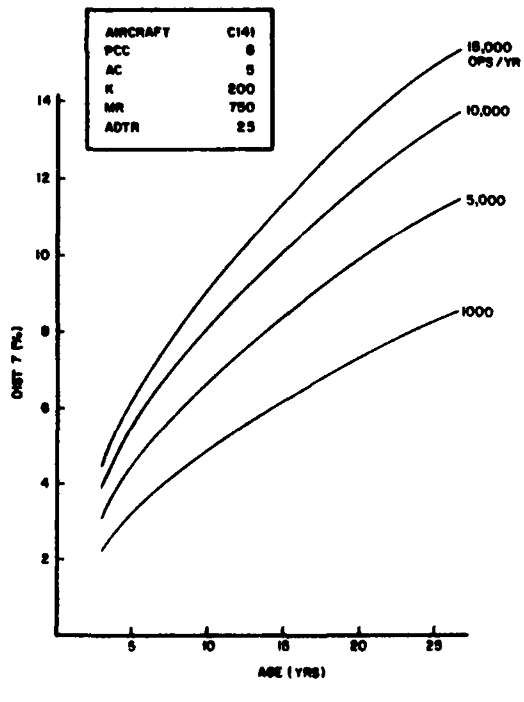

Figure 58. Effect of Traffic Volume on DIST7 (% Joint Reflection Cracking) as a Function of Age.

Figure 60 shows the effect of varying PCC amounts. Again, there is not a large change in predicted amounts of cracking with changes in PCC thickness. The model suggests that joint reflection cracking will occur, irrespective of pavement thickness.

c. Environment

Environment is represented by the average daily temperature range (IADTR) variable. The power function of the variable seems to suggest that cracking will occur quickly and that the total amount will level off (the variable is a function of the square root of age). The square power on the ADTR portion of the variable indicates that changes in ADTR significantly affect the amount of cracking. Figure 61 shows the powerful influence of average daily temperature range.

d. Pavement Condition Before Overlay

Both age before overlay and previous maintenance are considered here. It is known that the condition of a PCC pavement just before overlay, particularly the condition of the joints, will greatly influence the pavement performance after overlay. Whether the joints are open and raveled or filled in will influence how quickly the joint will reflect through asphalt. Since there was no data on the condition of the joints, or even the pavement as a whole before the overlay, it was hoped that the age before overlay or general maintenance might indicate the condition of the joints. However, no information was available and the model is deficient in this area.

E. ALLIGATOR CRACKING

Data for developing a predictive model for alligator cracking were collected for 69 cases; of these, 43 features had been overlaid at least once. The average value for DIST 1 (percent of low-, medium-, and high-severity alligator cracking) was found to be 1.41 percent. Figure 62 gives a numerical breakdown of the amounts of DIST1 found; over half of the sections showed no signs of alligator cracking. Also, of the 35 features with no distress, 14 were overlaid.

Alligator cracking is a distress which was somewhat difficult to predict. The model that was developed did not predict alligator cracking well between 0 and 5 percent. Since that was the predominant range in which alligator cracking was observed (and used to develop the model), this model was determined to be unacceptable.

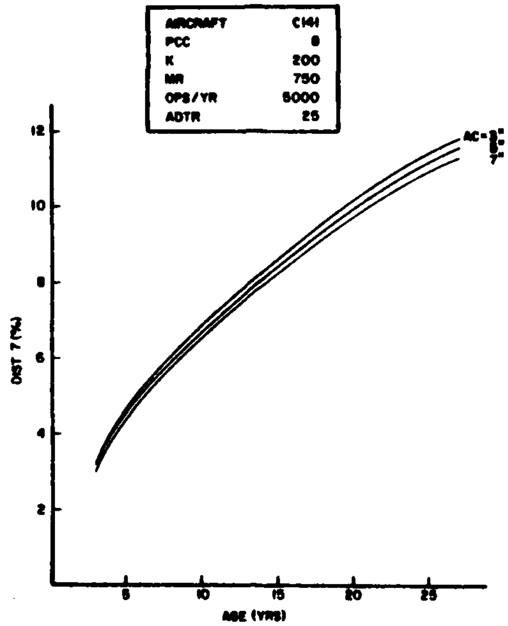

Figure 59. Effect of Asphalt Overlay Thickness on DIST7 (% Joint Reflection Cracking) as a Function of Age.

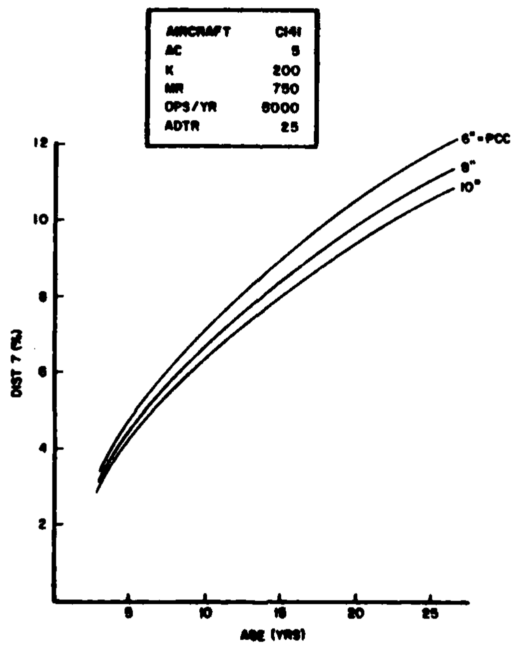

Figure 60. Effect of PCC Thickness on DIST7 (% Joint Reflection Cracking) as a Function of Age.

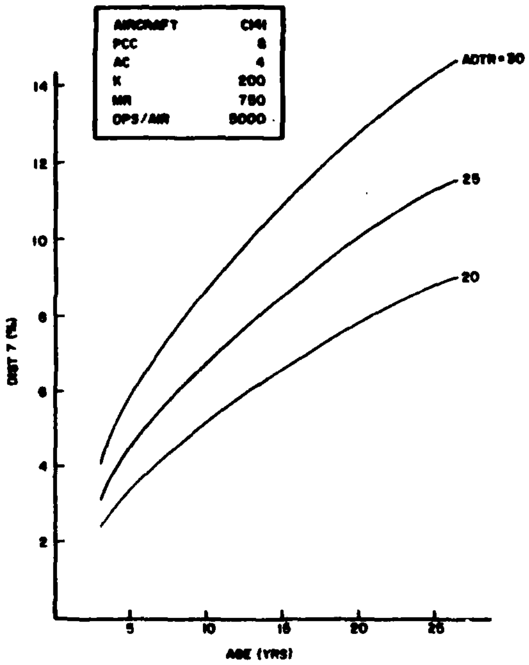

Figure 61. Effect of Average Daily Temperature (^{o}F) on DIST7 (% Joint Reflection Cracking) as a Function of Age.

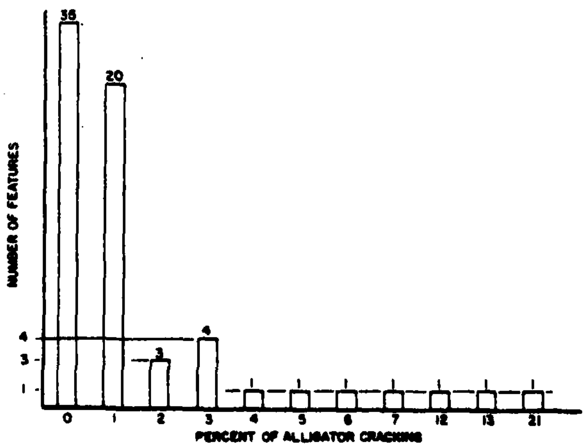

Figure 62. Histogram of the Percentage of Sections Affected by Alligator Cracking.

SECTION V

DATA COLLECTION FOR MODEL VERIFICATION

New airfield pavement data were obtained from five of the 12 Air Force bases (see Figure 63) surveyed during FY 80. The new data would serve two purposes: (1) verification of the existing models, and (2) obtaining information on the progression of distresses and on PCI trends over time.

Data were collected on the same set of data sheets used for the FY 80 data collection. The same data used in FY 80 was often applicable to FY 82 sections. This eliminated having to collect a complete set of historical information for most pavement features. The data included all historical data obtained from FY 80, plus:

1. Information on new pavement layers

2. New or updated traffic information (type, annual operations)

3. Major maintenance efforts

4. Current PCI and distress surveys.

Appendix A provides copies of the data collection sheets and coding sheets.

A. DATA COLLECTION PROCEDURES

The five Air Force bases surveyed in FY 82 were selected as being representative of the 12 bases surveyed during FY 80. New data were obtained for similar pavement types, range of climatic variables (precipitation, temperatures, freezing index), and traffic. Data were collected for 101 features and divided into the following pavement types:

	FY 82 % Features	FY 80 % Features
PCC	61	60
PCC/PCC	0	1
PCC/AC	2	1
AC	6	10
AC/PCC	8	9
AC/AC	23	18
Other	0	1
	100%	100%

Surveys were performed on runways, taxiways, and aprons, with most sections located on taxiways. The features surveyed were:

	FY 82 % Features	FY 80 % Features
Runways	34	35
Taxiways	48	46
Aprons	18	19
	100%	100%

These figures show that the FY 82 and FY 80 data are very similar. Table 11 gives a breakdown of the different pavement types at each base.

Some inconsistencies were found between the FY 80 and FY 82 data; however, in most cases, the data seemed reasonable. For example, a few features had PCIs which increased over time, but most were within an accepted range of $\pm$ 5 points. Table 12 lists the PCI values obtained from the FY 80 and FY 82 data.

The new data were obtained from the same sources used in FY 80: Air Force evaluation reports, construction records, and recollections of employees, plus FY 80 data. The traffic data were also compared for FY 80 and FY 82 and seemed reasonable; however, it should be remembered that all traffic data are approximate.

B. DATA PROCESSING

All data were checked carefully to correct errors and to locate missing information. Means, frequencies, and other statistics were obtained to further verify the reasonableness of the data. Tables 13 and 14 summarize the key concrete and asphalt variables. The means and ranges of these values are very similar to those of the FY 80 data. Histograms show the distribution of variables for (1) PCC (Figures 64 through 70), (2) AC and AC/AC pavements (Figures 71 through 80), and (3) AC/PCC pavements (Figures 81 through 89).

The average life of an asphalt surface was also compared using the FY 80 and FY 82 data; Figures 28 and 90 show that the two data sets yielded the same results. On the average, a given asphalt surface will last much longer than subsequent asphalt surface.

Figure 63. Illustration of Geographical Spread of Data for FY 82 Survey, Including Bases Surveyed in FY80.

TABLE 11. NUMBER OF FEATURES SURVEYED WITH RESPECTIVE PAVEMENT TYPE.

AFB	PCC	PCC/AC	AC	AC/PCC	AC/AC	TOTALS
Dover	6	2	0	3	6	17
Hill	13	0	5	0	3	21
Holloman	12	0	1	0	8	21
Mt. Home	12	0	0	1	4	17
Robins	18	0	0	5	2	25
TOTALS	61	2	6	9	23	101
%	61	2	6	8	23	100

TABLE 12. COMPARISON OF PCI VERSUS TIME FOR FEATURES FROM THE FIVE BASES SURVEYED IN 1982.

		PCI				PCI				PCI	
BASE	Feature	1980	1982	BASE	Feature	1980	1982	BASE	Feature	1980	1982
Dover	2	94	68	Holloman	1	58	53	Robins	1	75	79
	3	88	84		2	28	45		2	78	76
	6	71	63		3	50	35		3	72	77
	7	79	31		4	47	62		4	88	85
	8	87	77		5	59	65		5	84	87
	9	54	64		6	72	77		6	77	72
	10	64	80		7	67	80		7	77	79
	11	71	77		9	92	87		8	65	75
	13	74	55		13	82	82		10	69	84
	17	99	78		14	65	72		11	64	86
	18	69	50		15	24	30		12	59	87
	19	99	84		16	76	60		13	71	89
	20	97	90		17	80	83		14	79	75
	21	47	16		18	72	83		15	72	81
	22	71	58		19	74	70		16	77	80
	23	97	95		23	79	73		17	77	81
	28	58	65		25	97	97		18	74	79
					26	78	87		20	78	75
Hill	1	53	64		27	78	80		21	79	66
	2	84	85		28	71	71		22	79	66
	3	82	76		29	80	80		23	77	98
	4	66	55						24	69	73
	5	98	74	Mt. Home	1	66	59		25	79	98
	6	69	70		2	74	61		28	81	92
	7	50	56		3	88	80		29	78	71
	8	79	65		4	81	81				
	9	89	92		5	89	91				
	11	53	64		6	87	83				
	12	58	70		7	79	77				
	13	94	70		8	81	91				
	14	67	58		9	81	90				
	15	84	76		10	54	40				
	16	63	63		11	65	37				
	17	86	86		12	74	38				
	18	44	44		13	71	63				
	19	60	60		14	94	84				
	20	100	100		17	93	91				
	21	100	100		18	59	62				
	23	95	95		20	49	36				

NOTE: Routine maintenance or placement of an overlay would cause the PCI to increase over time. Also, the confidence level for the PCI is ± 5 points. Therefore, an increase in the PCI of 10 points would still be acceptable.

TABLE 13. MEANS AND RANGES OF KEY CONCRETE PAVEMENT VARIABLES* COLLECTED FOR MODEL VERIFICATION AT 63 AIRFIELD FEATURES ON FIVE AIR BASES.

	Mean Value	Range
Layer Information Variables		
AGE -- years	23.1	2-40
PCC THICKNESS -- inches	15.5	6-23
MODULUS OF RUPTURE -- psi	704	450-992
BASE MATERIAL+ -- coded	-	-
BASE THICKNESS+ -- inches	13.7	4-48
SUBGRADE MATERIAL -- coded**	-	-
MODULUS OF SUBGRADE REACTION (K)++ -- pci	202	50-400
Environmental Variables		
AVERAGE ANNUAL TEMPERATURE -- °F	57.3	50.9-65.1
AVERAGE ANNUAL PRECIPITATION -- inches	25.1	10.6-44.5
FREEZING INDEX -- degree days	39.4	0-274
FREEZE-THAW CYCLES -- 2 inch depth	48.7	0-111
WATER TABLE -- Ft	172	5-500
Discrete Variables		
FEATURE TYPE -- coded**	-	-
CRACK FILLING POLICY -- coded**	-	-
PRIMARY OR SECONDARY -- coded	-	-
Mechanistic Variables		
FATIGUE	121,225	338-717722
DAMAGE	682.13	0-24,952

*Does not include concrete pavements overlaid with asphalt.
**Means and ranges not applicable to coded variables.
+Mean value does not include those features with no base course (28 features had no base course).
++K-value on top of layer which PCC surface rests upon.

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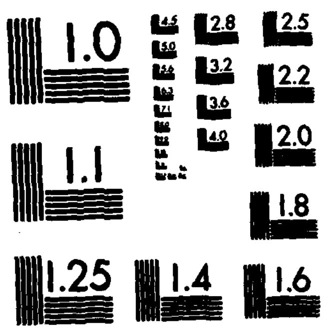

MICROCOPY RESOLUTION TEST CHART

TABLE 14. MEANS AND RANGES OF KEY ASPHALT PAVEMENT VARIABLES* COLLECTED FOR MODEL VERIFICATION AT 29 AIRFIELD FEATURES AT FIVE AIR BASES.

	Mean Value	Range
Layer Information Variables		
AGE -- years	8.79	0-21
ORIGINAL AC THICKNESS -- inches	3.85	2.0-6.0
TOTAL AC THICKNESS -- inches	6.32	4.0-10.0
BASE MATERIAL -- coded**	-	-
BASE CBR -- percent	83.97	58-100
TOTAL SELECT THICKNESS -- inches	29.59	0.0-67.0
SUBGRADE MATERIAL -- coded**	-	-
SUBGRADE CBR -- percent	19.48	6-60
Environmental Variables		
AVERAGE ANNUAL TEMPERATURE -- ^{o}F	55.7	50.9-65.1
AVERAGE ANNUAL TEMPERATURE RANGE -- ^{o}F	24.8	19.4-28.5
AVERAGE ANNUAL PRECIPITATION -- inches	20.5	10.6-44.5
AVERAGE ANNUAL SOLAR RADIATION -- langleys	422	335-520
FREEZING INDEX -- degree days	99	0-274
FREEZE-THAW CYCLES -- 2 inch depth	40.1	0-99
WATER TABLE -- feet	191	5-500
Discrete Variables		
FEATURE TYPE -- coded**	-	-
CRACK-FILLING POLICY -- coded**	-	-
PRIMARY OR SECONDARY -- coded**	-	-
Mechanistic Variables		
WEIGHTED AVERAGE SURFACE DEFLECTION (present period) -- (inches/ESWL)	.001	.001-.002
WEIGHTED AVERAGE SURFACE DEFLECTION+ (1st previous period) -- (inches/ESWL)	.001	0-.002
WEIGHTED AVERAGE VERTICAL STRESS ON BASE (present period) -- psi	85.	124-175
WEIGHTED AVERAGE VERTICAL STRESS ON BASE* (1st previous period)+ -- psi	71.3	0-163
CUMULATIVE VERTICAL STRESS ON BASE (present period) -- (psi x no. of passes)	3.04×10^{7}	$1.34 \times 10^{6}-1.52 \times 10^{8}$
CUMULATIVE VERTICAL STRESS ON BASE (1st previous period)+ -- (psi x no. of passes)	2.02×10^{7}	$0-1.26 \times 10^{8}$
CUMULATIVE VERTICAL STRAIN ON SUBGRADE (present period) -- (0.001 inches/inch x no. of passes)	1.55×10^{6}	$14100-1.09 \times 10^{7}$
CUMULATIVE VERTICAL STRAIN ON SUBGRADE (1st previous period)+ -- 0.001 inches/inch x no. of passes)	1.20×10^{6}	$0-1.03 \times 10^{7}$

*Does not include asphalt overlaid concrete pavements.
**Means and ranges not applicable to coded variables.
+A period is defined by the age of the surface or overlay. (See Figure 29 for diagram.) If no overlay exists and therefore there is no previous period, the value for this variable for that particular feature is recorded as 0. These features are included in the calculation of the mean value.

PCC PAVEMENTS

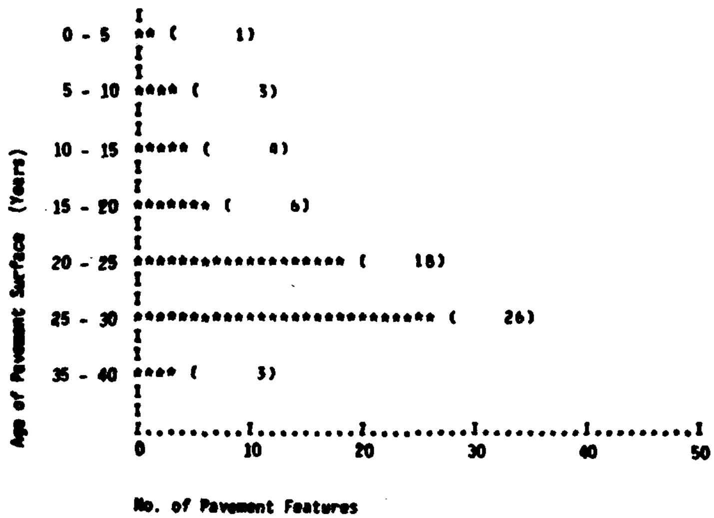

Figure 64. Histogram of PCC Pavement Age in Years Since Last Construction.

PCC PAVEMENTS

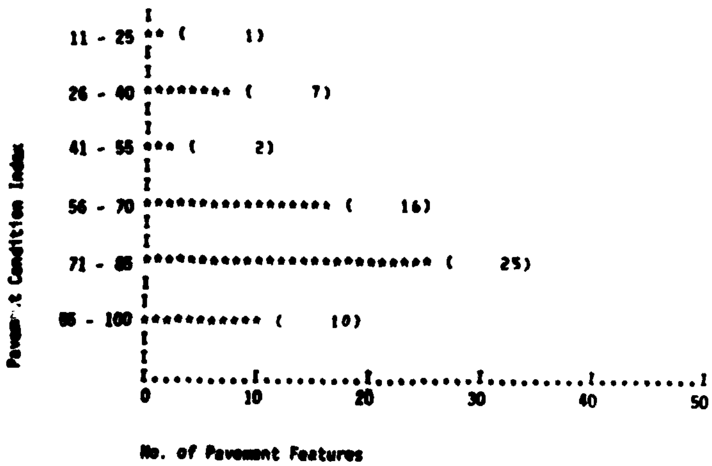

Figure 65. Histogram of PCC Pavement Feature PCI.

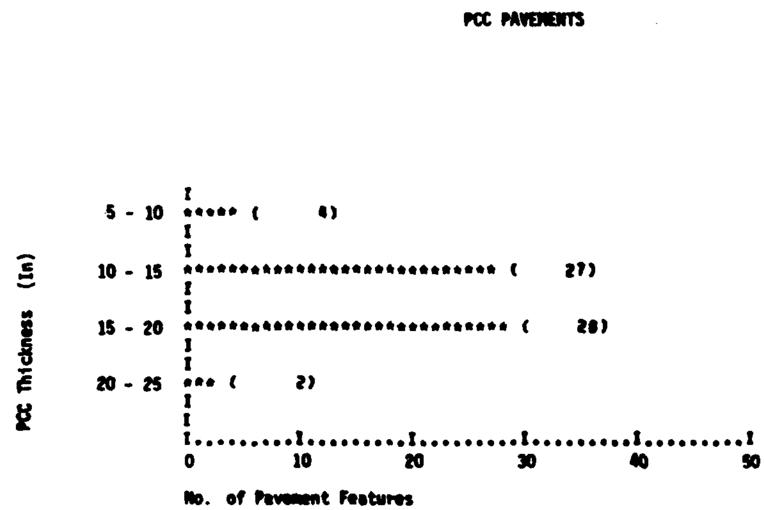

Figure 66. Histogram of PCC Surface Thickness in Inches.

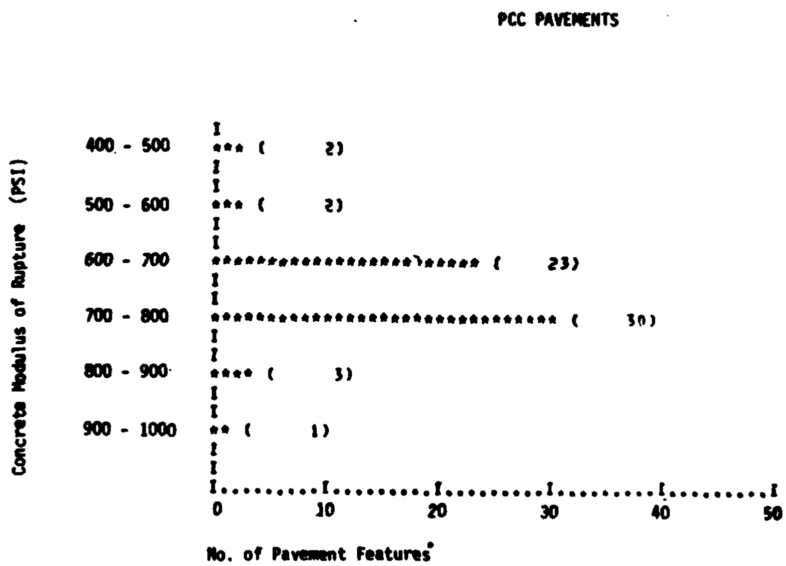

Figure 67. Histogram of Modulus of Rupture of Concrete in Pounds per Square Inch (PCC Pavement).

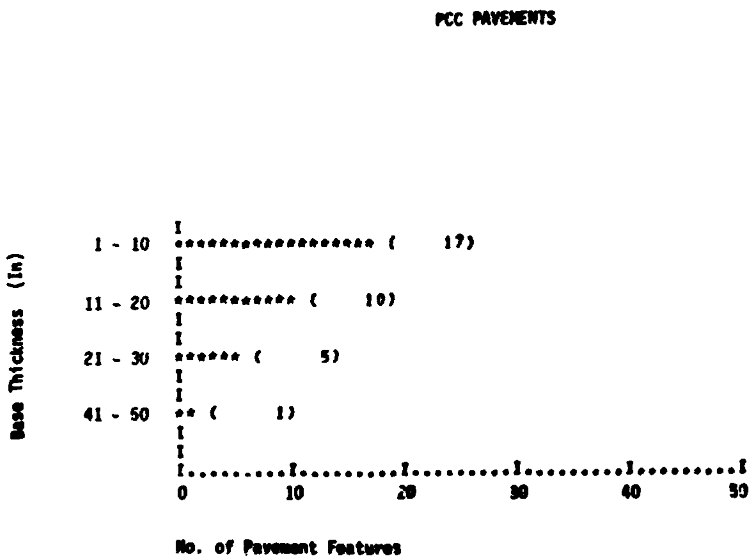

Figure 68. Histogram of PCC Pavement Base Course Thickness in Inches.

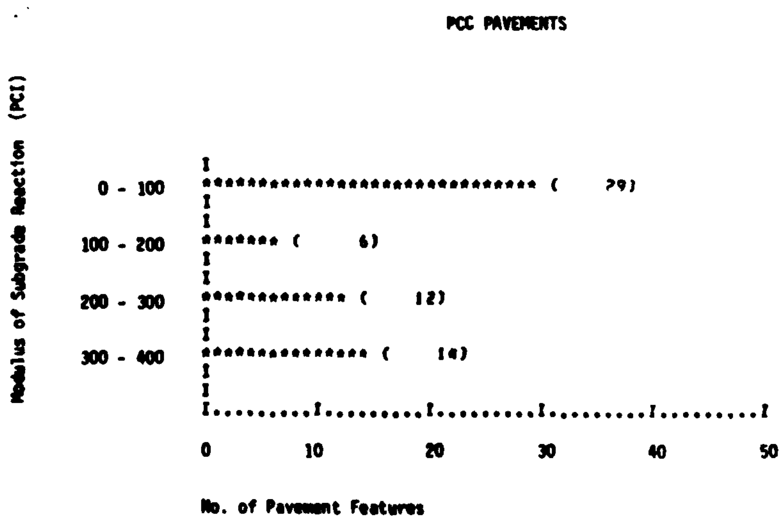

Figure 69. Histogram of PCC Pavement Modulus of Subgrade Reaction in Pounds per Cubic Inch.

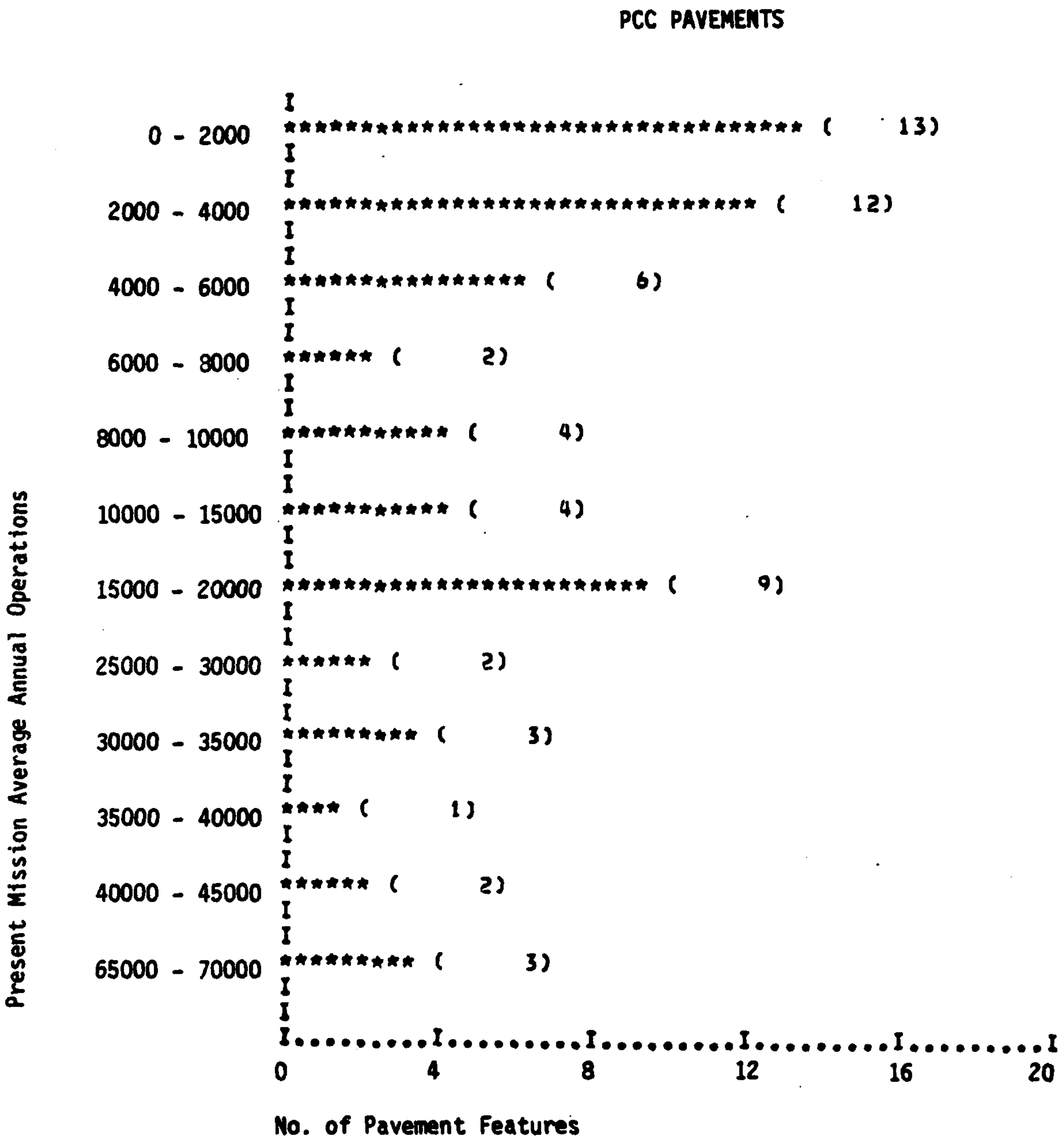

Figure 70. Histogram of Average Annual Volume of Traffic on PCC Pavement.

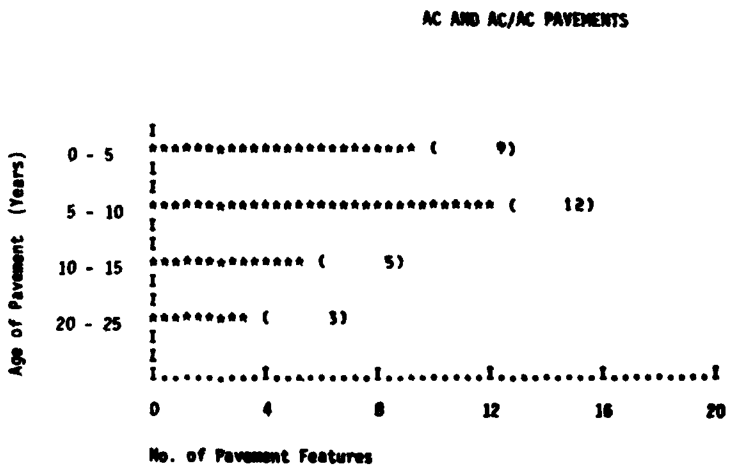

Figure 71. Histogram of AC and AC/AC Pavement Age in Years Since Construction of Last Overlay.

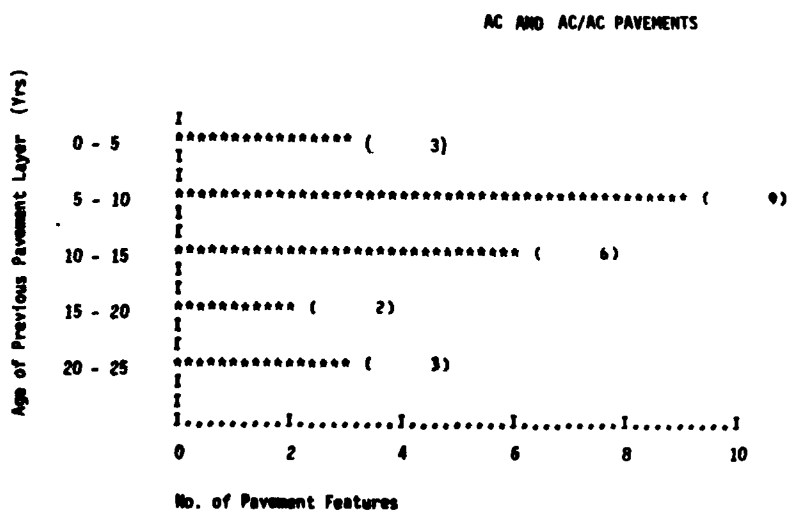

Figure 72. Histogram of Age of Previous Pavement Layer (AGECOL) in Years for AC and AC/AC Pavement. (NOTE: 6 AC Pavements Have Not Been Overlaid.)

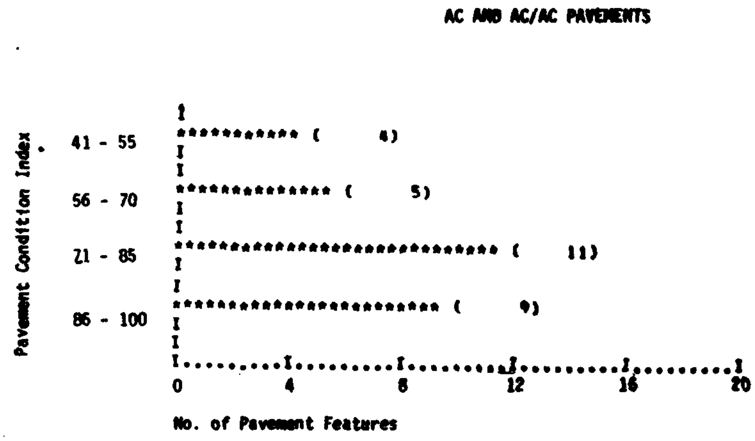

Figure 73. Histogram of AC and AC/AC Pavement Feature PCI.

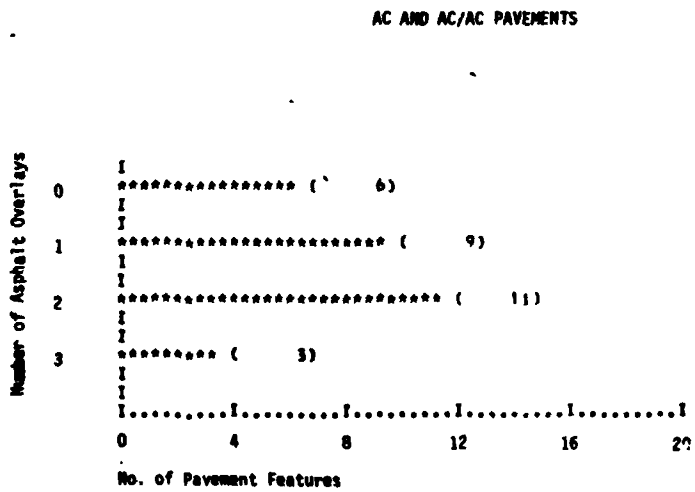

Figure 74. Histogram of Number of Overlays for AC and AC/AC Pavement.

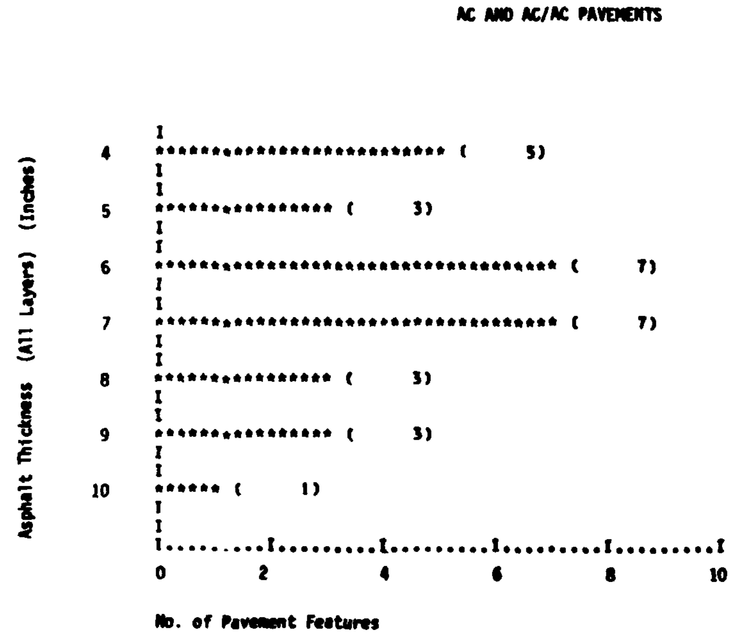

Figure 75. Histogram of AC and AC/AC Pavement Total Asphalt Thickness in Inches.

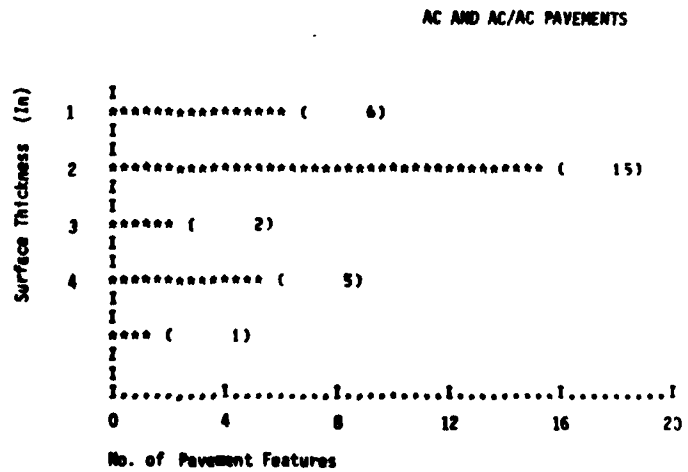

Figure 76. Histogram of AC and AC/AC Pavement Surface Thickness in Inches.

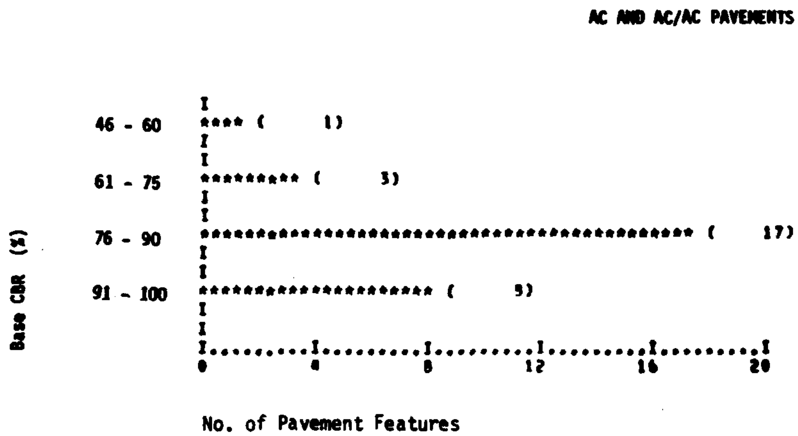

Figure 77. Histogram of AC and AC/AC Pavement Base Course California Bearing Ratio (CBR) Percent.

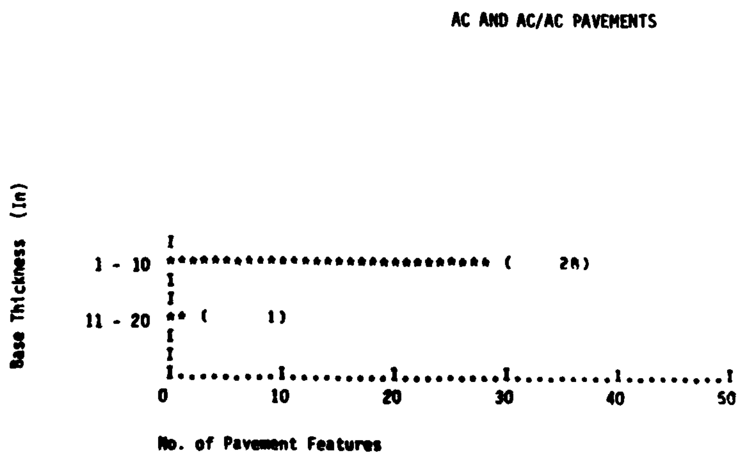

Figure 78. Histogram of AC and AC/AC Pavement Base Course Thickness in Inches.

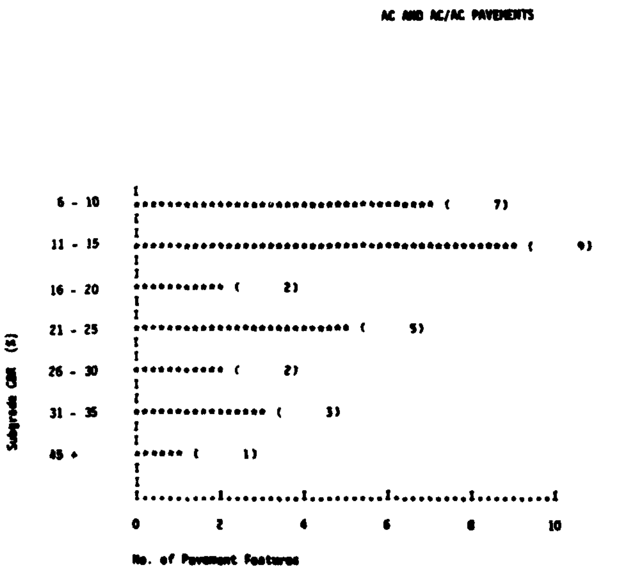

Figure 79. Histogram of AC and AC/AC Pavement Subgrade California Bearing Ratio (CBR) Percent.

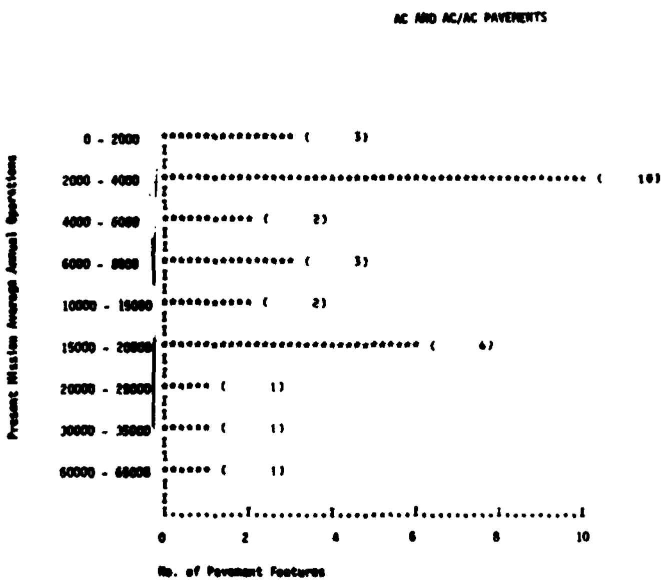

Figure 80. Histogram of Average Annual Volume of Traffic on AC and AC/AC Pavement.

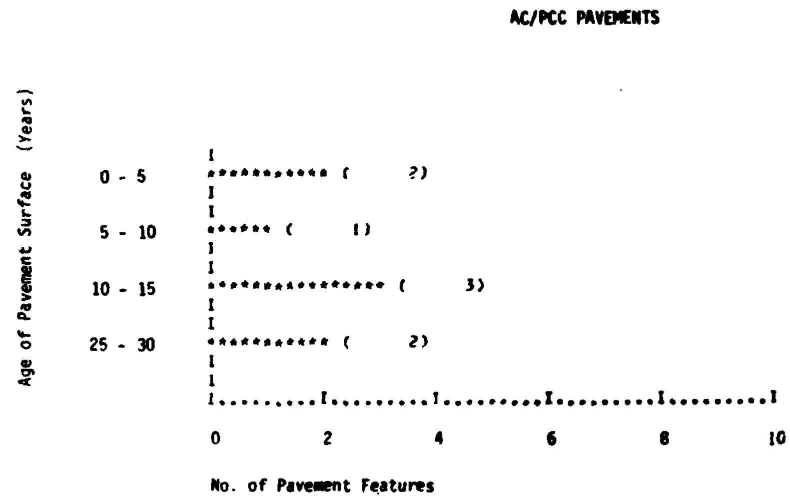

Figure 81. Histogram of AC/PCC Pavement Age in Years Since Last Overlay.

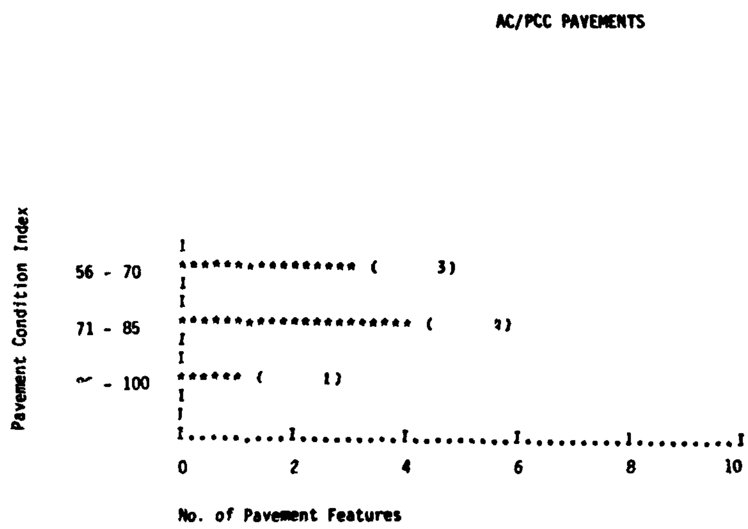

Figure 82. Histogram of AC/PCC Pavement Feature PCI.

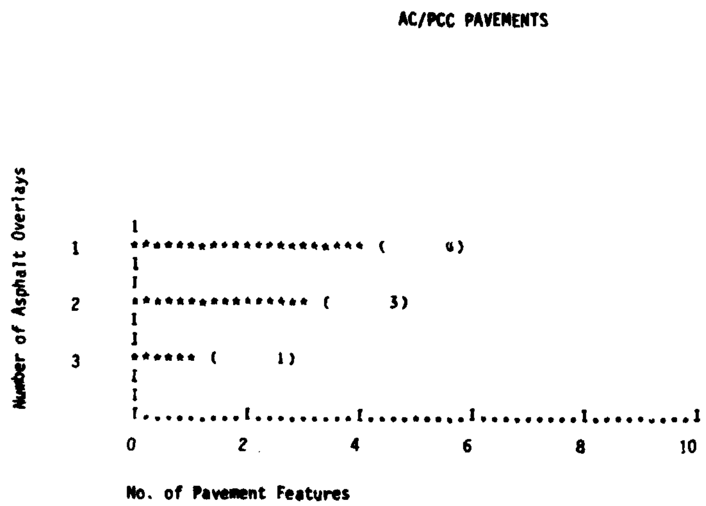

Figure 83. Histogram of Number of Asphalt Overlays for AC/PCC Pavement.

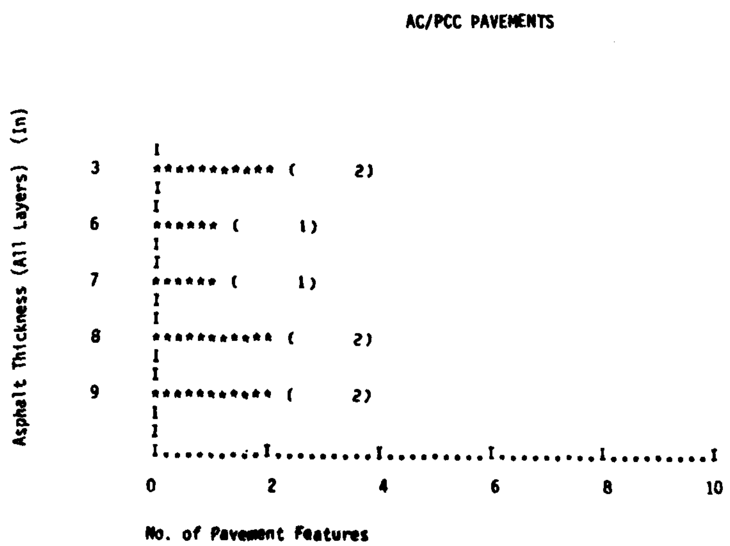

Figure 84. Histogram of AC/PCC Pavement Total Asphalt Thickness in Inches.

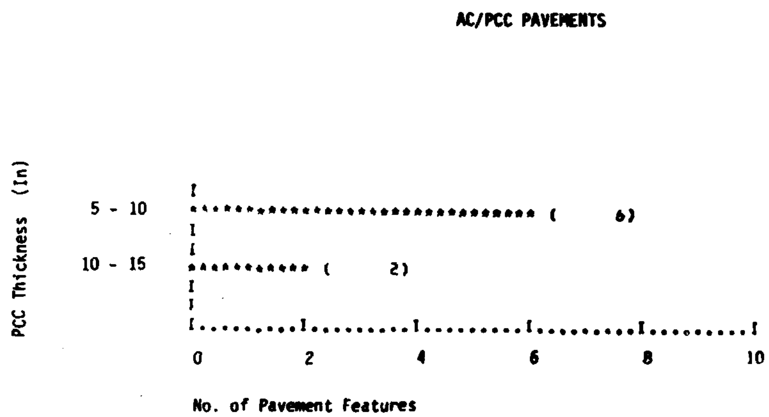

Figure 85. Histogram of AC/PCC Pavement Concrete Thickness in Inches.

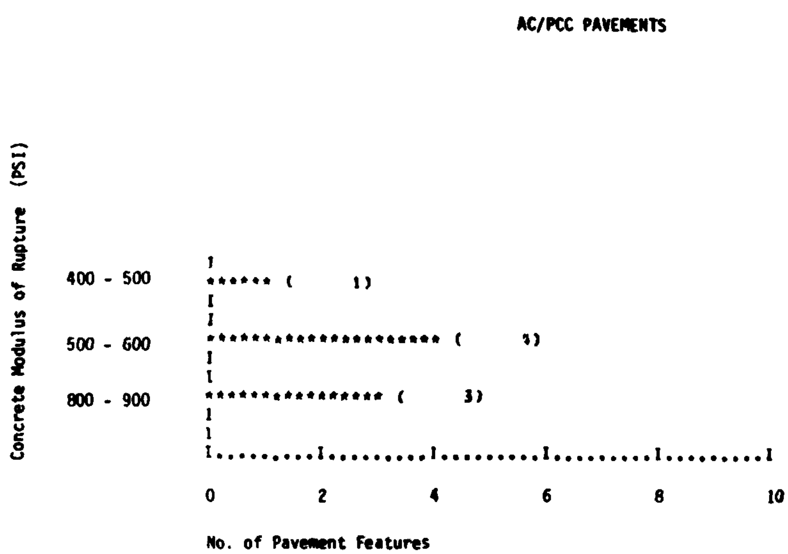

Figure 86. Histogram of Modulus of Rupture of Concrete in Pounds per Square Inch (AC/PCC Pavement).

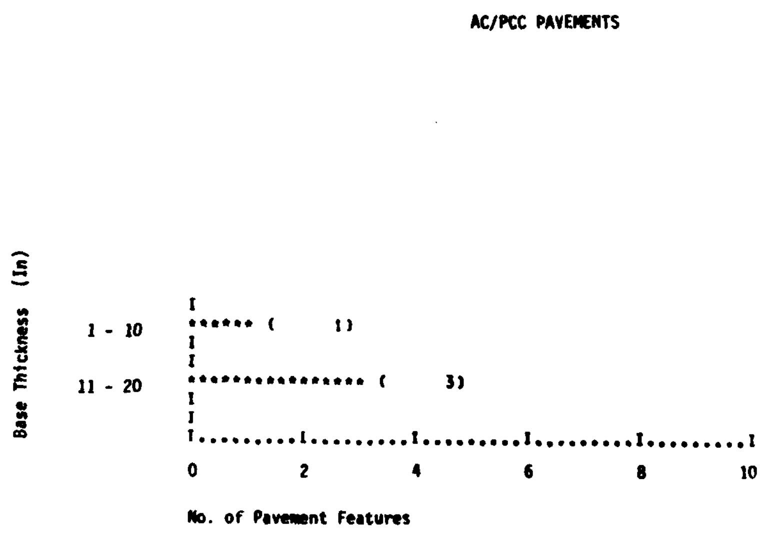

Figure 87. Histogram of AC/PCC Pavement Base Course Thickness in Inches.

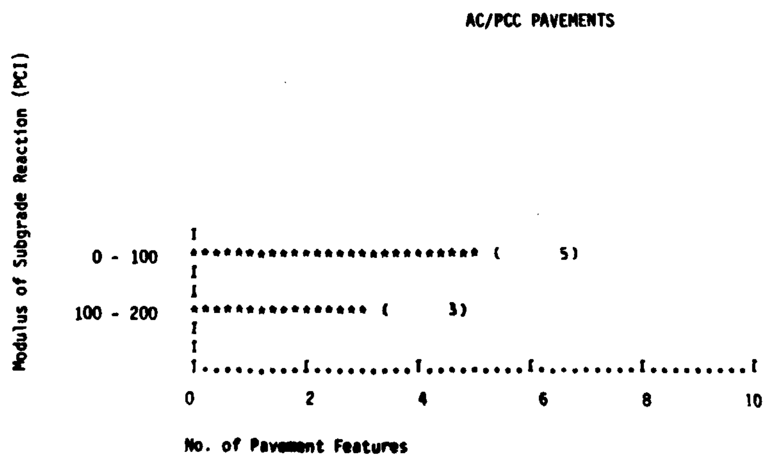

Figure 88. Histogram of AC/PCC Pavement Modulus of Subgrade Reaction in Pounds per Cubic Inch.

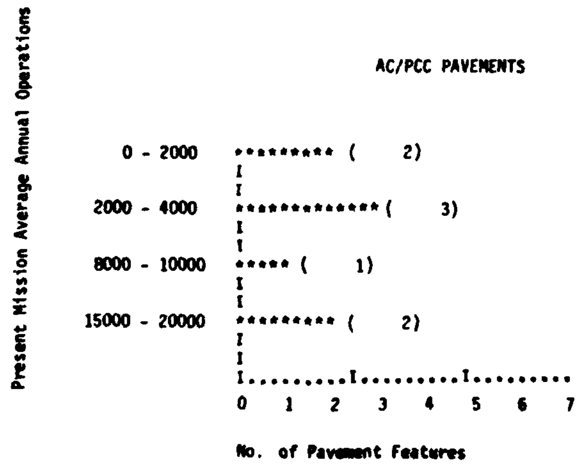

Figure 89. Histogram of Average Volume of Traffic on AC/PCC Pavement.

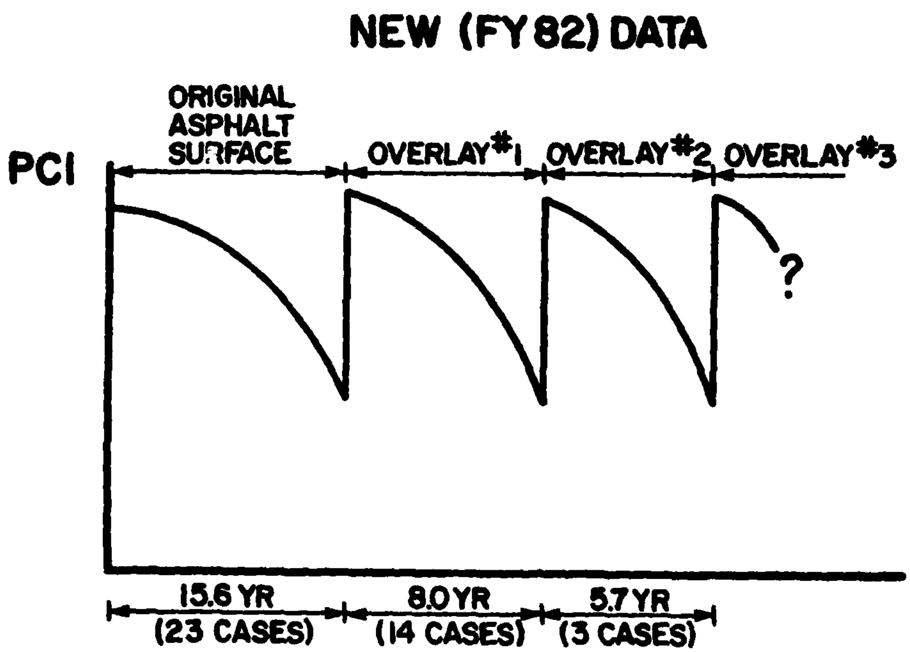

Figure 90. Average Age of an Asphalt Surface Before Getting Overlaid.

SECTION VI

MODEL VERIFICATION

The main purpose of collecting new data from the pavement features surveyed in FY80 was to verify the models' ability to predict pavement performance (e.g., the PCI or a distress quantity). The new data were not used to develop models.

The input variables used to develop the prediction models (FATAGE, DAMAGE, AGECOL) were computed for the new data and input into the models to obtain the predicted value of the dependent variable. Table 15 summarizes the relationship between the actual and predicted values for all the models. Scattergrams were also generated using SPSS (Reference 11) to illustrate the scatter in the relationship between the actual and predicted values. Ideally, all predicted values would equal the actual values; however, the scatter of points does show inadequacies, either in the model or in the actual data. The following section briefly describes each model verification.

A. PCC AND AC/PCC PCI MODEL VERIFICATION

The PCI model, for concrete and asphalt-overlaid concrete pavements was verified using FY82 data. Overall, the model's capabilities seem encouraging. However, it does a good job of predicting the PCI (see Figure 91) only when the PCI is 50 or greater. One reason is that there are not enough data points where the PCI is less than 50. The R^2 of this model is .61, and the standard deviation is 12.1.

Figure 92 shows that this model does an exceptional job of predicting the PCI at Robins AFB; the statistics (R^2 = .834, σ = 4.88) reveal that the model does a better job of predicting the PCI for Robins than for any other base. However, Figure 93 shows that this model is not adequate for predicting the PCI at Dover AFB. The standard deviation (17.69) is so poor that there could be no confidence in the model for Dover AFB. Therefore, it is suggested that the concept of localized modeling (a model developed for only one base) be incorporated. Such a model could provide vastly improved statistics. Localized modeling should be able to eliminate the inconsistencies, both for traffic data among bases and for climatic effects, which are difficult to model. Inadequacies in the PCI model include:

1. Bad prediction when the PCI < 50

2. Lack of standardized traffic data count

3. Climatic conditions for Dover may not be as well reflected as for Robins.

Table 16 summarizes the statistics of the model verification, base by base.

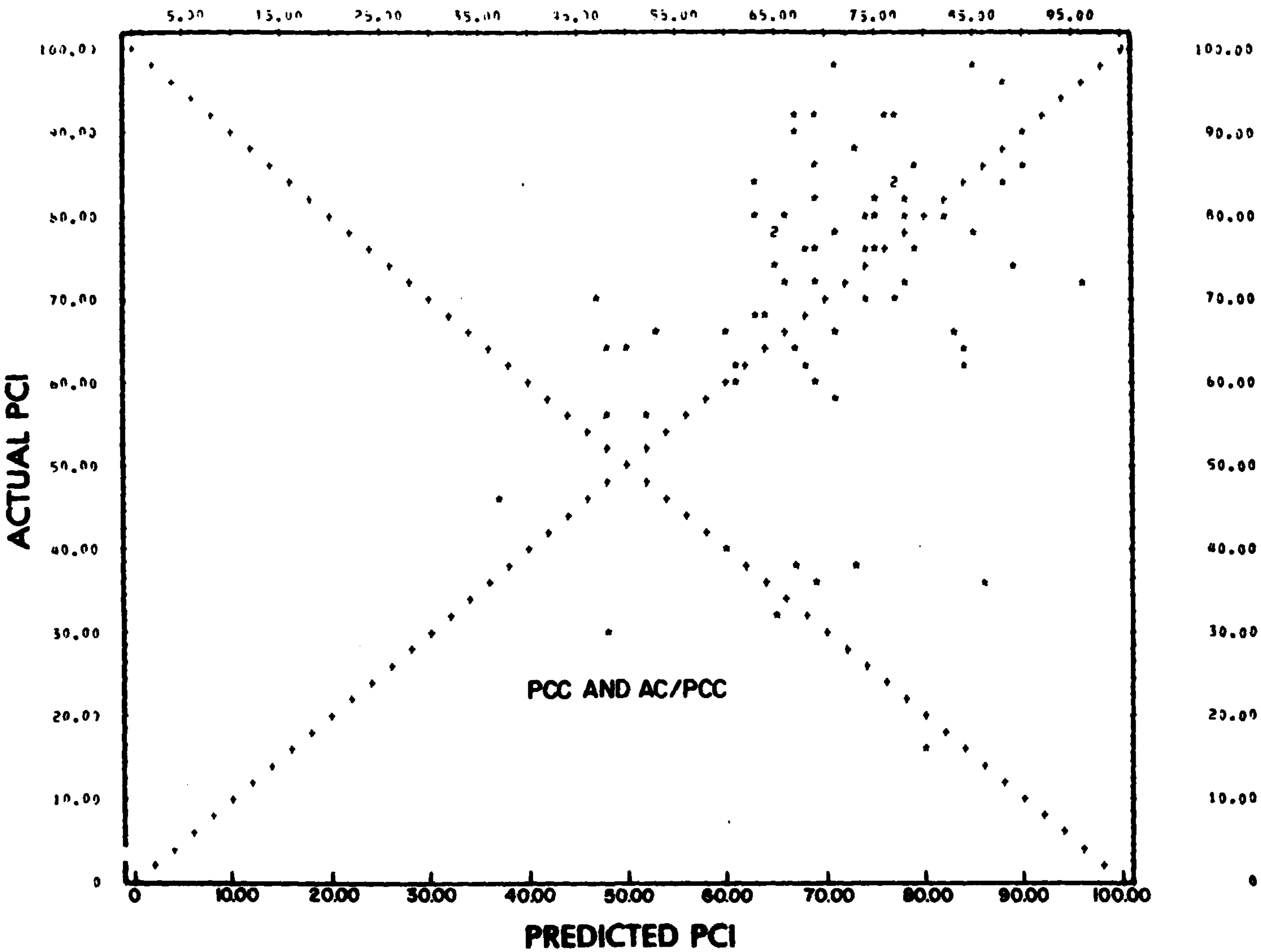

Figure 91. Scattergram of Actual PCI vs. Predicted PCI Using FY82 Data and Model Presented in Section III.

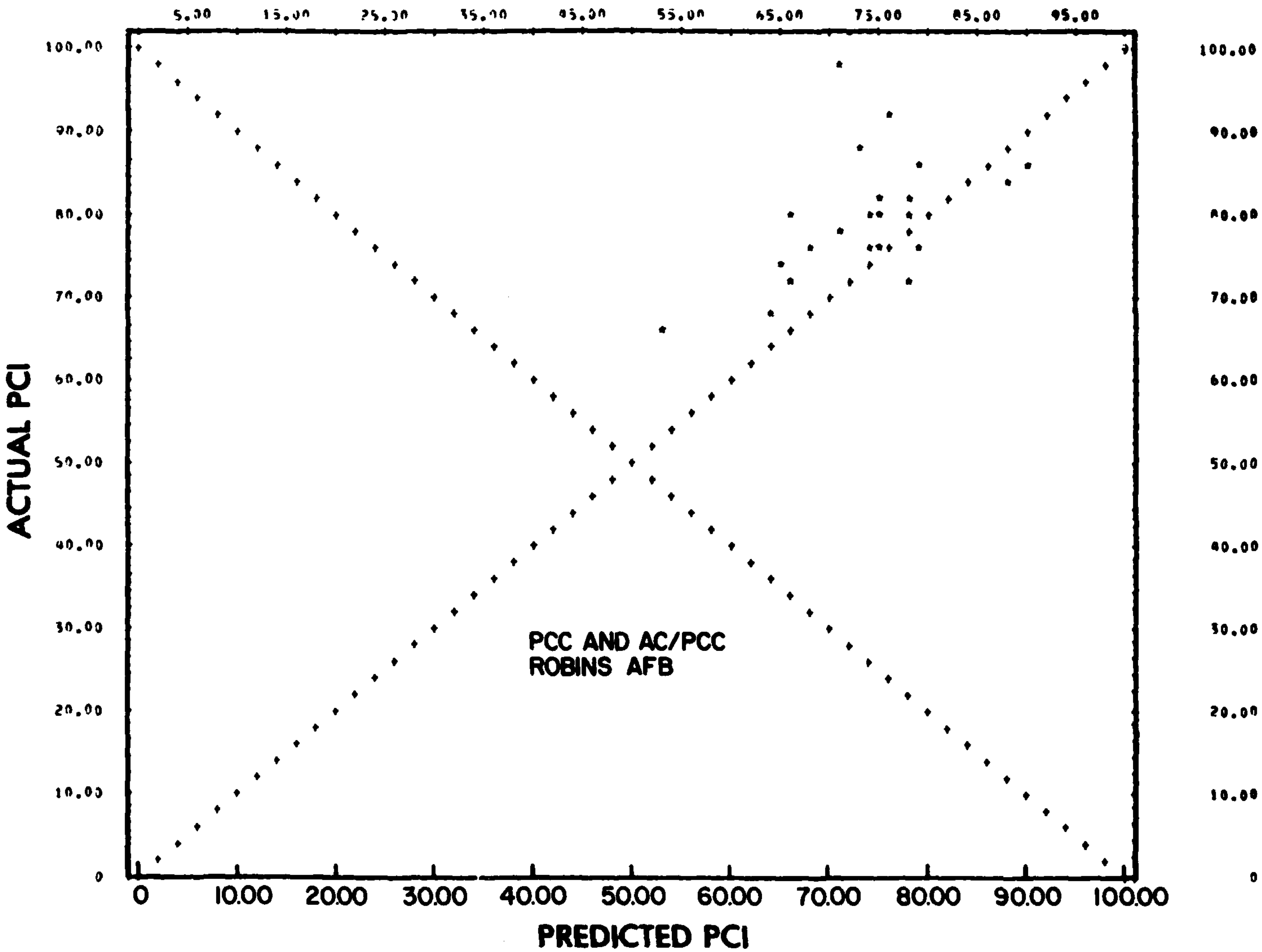

Figure 92. Scattergram of Actual PCI vs. Predicted PCI Using Robins AFB FY82 Data and Model Presented in Section III.

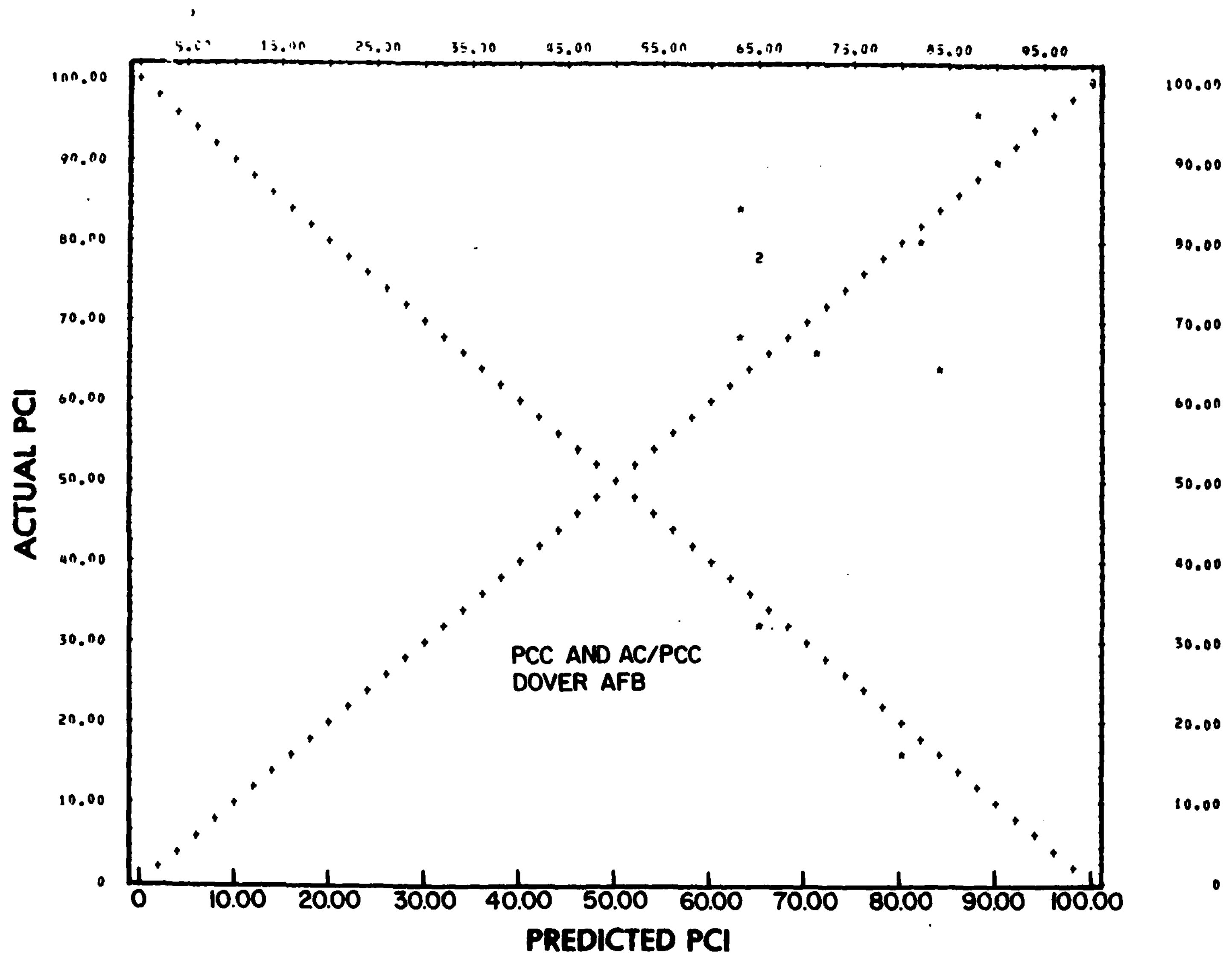

Figure 93. Scattergram of Actual PCI vs. Predicted PCI Using Dover AFB FY82 Data and Model Presented in Section III.

TABLE 15. SUMMARY OF STATISTICS FOR MODELS DEVELOPED AND MODELS VERIFIED.

Dependent Variable of Model	Model Development (FY80 Data) R^2*	Std Dev.	No. Cases	Model Verification (FY82 Data) R^2*	Std Dev.	No. Cases
PCI (PCC and AC/PCC)+	0.741	8.12	318**	0.696	9.98	138**
Corner Break (PCC)	0.797	1.64%	137	0.251	4.65%	63
PCI (AC and AC/AC)+	0.833	7.20	138**	0.810	6.96	58**
Reflection Cracking	0.739	2.42%	25	0.262	2.18%	8

*R^2 of actual value compared with value predicted using model developed from FY 80 data.
**Includes all duplicated cases (i.e., for each surveyed feature, the PCI was assumed to be 100 at age = 0).
+Model developed using duplicated data.

B. CORNER BREAK MODEL VERIFICATION

The corner break model seems to be inadequate when using the new data to verify the predicting capabilities (see Figure 94). Unfortunately, only nine sections from the new data exhibited any corner breaking, and the model did a poor prediction job on these cases. The model also overpredicted distress levels by 1 to 5 percent for most of the cases exhibiting no distress. One reason for the poor performance of this model may be the range of corner breaking provided by the data used to develop the model (predominantly 0 to 3 percent).

C. AC AND AC/AC PCI MODEL VERIFICATION

Figure 95 is a scattergram of the predicted versus the actual PCI. When using duplicated data (half the data at PCI = 100, when age = 0), the model does a remarkably good job in predicting the PCI, both for the new data and the FY 80 data. In verification, the model does very well (see Table 15), even when duplicated data are not used. The scattergram using no duplicated data is exactly the same as the one using duplicated data except that there is not a glut of cases at PCI = 100 when the predicted PCI = 100. The glut of cases shown at one point means that all the variables in the PCI model include AGE; since age is assumed to be zero, the PCI assumes the constant of 99.82 (see the PCI equation in Section IV).

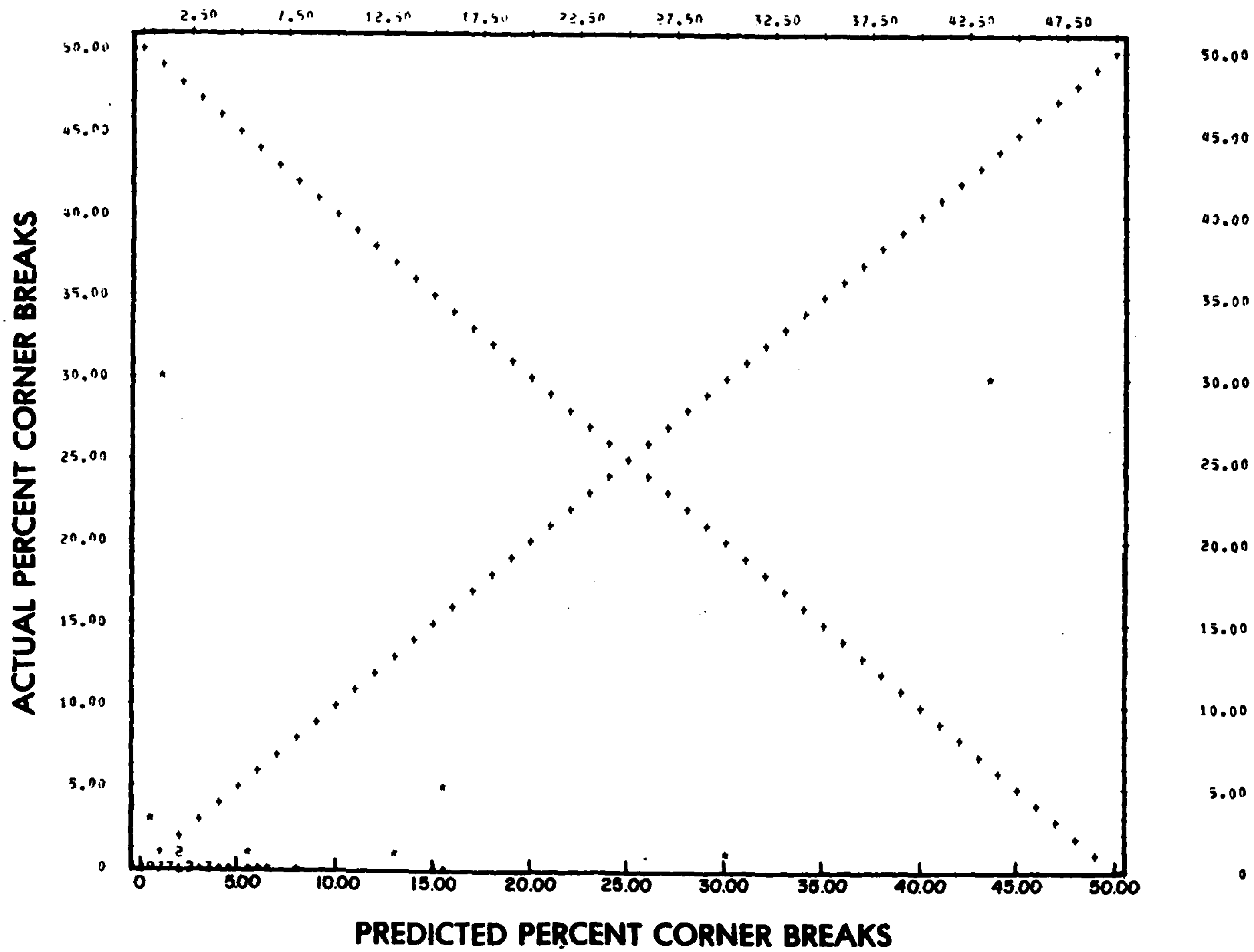

Figure 94. Scattergram of Actual Percent of Corner Breaking vs. Predicting Percent of Corner Breaking Using FY 82 Data and Model Presented in Section III.

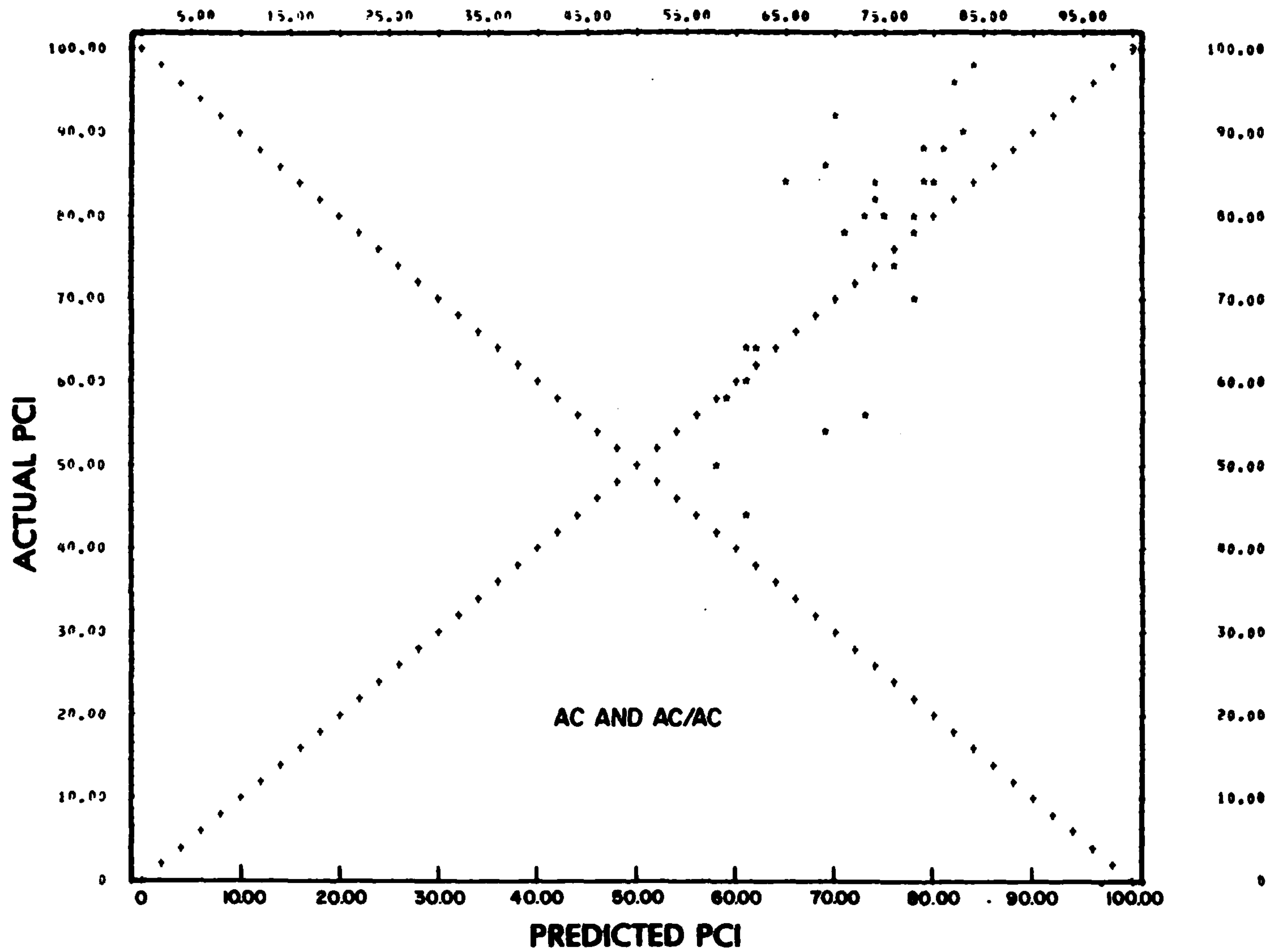

Figure 95. Scattergram of Actual PCI vs. Predicted PCI Using FY 82 Data and Model Presented in Section IV.

TABLE 16. STATISTICS FOR THE PCI MODEL FOR PCC AND AC/PCC PAVEMENTS USING PCI MODEL DEVELOPED IN SECTION III.

	Model Development* (FY 80 Data)			Model Verification* (FY 80 Data)		
	R^2	Std. Dev.	Cases	R^2	Std. Dev.	Cases
12 AFB (FY 80 Data)	.741	8.12	318	-	-	-
5 AFB (FY 82 Data)	-	-	-	.697	9.96	138
Dover	.639	8.55	32	.640	11.43	20
Hill	.869	6.22	32	.806	7.83	22
Holloman	.783	10.83	22	.754	10.66	22
Mt. Home	.783	8.26	34	.642	14.46	26
Robins	.828	5.92	56	.827	4.96	44

*Duplicated data used.

As with model development, the model verification scattergram also showed signs of slightly overpredicting the PCI when the actual PCI is below 60. Above 60, the model tended to underpredict the PCI. This problem needs to be investigated further, a possible solution being the implementation of localized modeling (see Section VII).

D. REFLECTION CRACKING MODEL VERIFICATION

The model does a very good job of predicting joint reflection cracking for AC/PCC pavements. Figure 96 is a scattergram of the actual data collected in FY 82 versus the value predicted by the model discussed in Section IV.

Most points were predicted at lower percentages than were actually found, possibly because of mechanistic factors that caused the joints to reflect through much more quickly than anticipated. It should be noted that the model did not include the condition of the joint before overlay.

The model may not represent all situations adequately, since only 25 cases were used to develop it However, the eight cases used to verify the model fit it very well, with the standard deviation being only 2.18 percent.

E. SUMMARY

The models developed for predicting the PCI can be used with confidence to predict network pavement performance. Both (1) the AC and AC/AC, and (2) the PCC and AC/PCC models performed satisfactorily. However, the PCC PCI model did not perform well when the PCI was less than 50, because very few data points were obtained for PCIs of less than 50. Very few airfield pavement sections have PCIs of less than 50, since a PCI of 50 is unacceptable for airfield pavements. Maintenance would probably have been done to upgrade the pavement and therefore increase the PCI.

When verifying the models, a few data points did not even come close to being predicted accurately. Thus, further investigation must be done to determine why these few points are not being properly modeled (e.g., for the PCC and AC/PCC model, eliminating cases where the PCI was less than 40 increased the R^2 of the model verification from .607 to .755 and decreased the standard deviation from 12.12 to 7.57). The models for predicting the PCI for a single base can be easily improved. By checking the developed models with data from a single base, it was shown that the models are much better suited to some specific bases; in all cases, developing one model for one base would be much better than using the universal model (developed with data from 12 bases).

Verification showed the AC joint reflection cracking model to be satisfactory. However, the civil base engineers should be cautious in implementing this model, since it was developed and verified with a small data population. Again, this model would be satisfactory for network analyses.

The corner break model was not satisfactory according to the new data and should not be used to predict pavement distress.

The use of the asphalt models hinges on the availability of BISAR (Reference 10) or any other computer program capable of calculating stresses, strains, and deflections in a multilayered, and deflections are determined, the fatigue and damage variables in the models can be calculated.

The use of the asphalt models hinges on the availability of BISAR (Reference 10) or any other computer program capable of calculating stresses, strains, and deflections in a multilayered, flexible pavement. Once the stresses, strains, and deflections are determined, the fatigue and damaged variables in the models can be calculated.

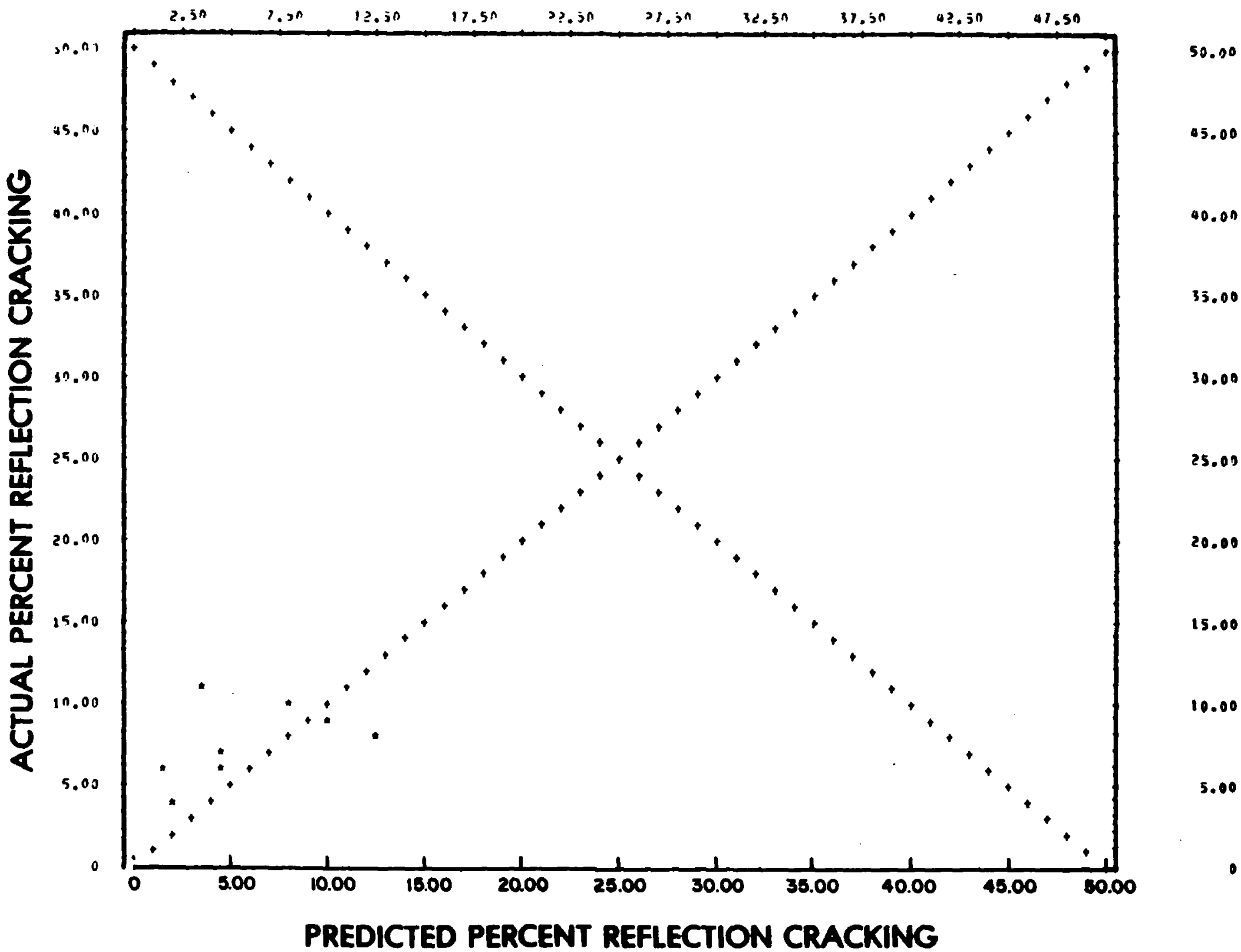

Figure 96. Scattergram of Actual Percent Joint Reflection Cracking vs. Predicted Percent Joint Reflection Cracking Using FY'82 Data and Model Presented in Section IV.

SECTION VII

LOCALIZED MODELING CONCEPT

During the model development phase of this project, it became apparent that there were problems with the collected data (despite extensive efforts in data collection and screening). Initial work in FY 78 showed that reliable prediction models could potentially be developed. Those data were less extensive than those collected for this study and early statistical analysis suggested that reasonable predictive models could be developed. However, as bases were added to the data bank, the statistics became less and less conclusive, and reasonable models became harder to achieve. It was clear that one major problem was the collected traffic data. To solve this problem, the basic prediction variables were narrowed down (by eliminating climatic and material variables which are constant at a given base), and prediction models were developed using a "base-by-base" approach for different bases. The new models were developed using the very same predictor variables used in the universal (12-base) model presented in Section III and only the coefficients of the variables were changed. PCI predictions for PCC and AC/PCC pavements for Dover and Robins AFB were used to develop the model. Table 17 summarizes the statistics. These two models do a better job of predicting the PCI for each respective base than the model presented in Section III.

Traffic seemed to be a large factor behind the results of the localized models. In gathering traffic information from each Air Force base, percentages and actual values of aircraft which use a specific pavement feature were gathered. The percentage breakdown of these results is probably more accurate than the absolute numbers, although much of the traffic data was obtained through the recollections of base personnel.

The following example clarifies why this effect tends to favor local modeling. Consider two different airfields (A and B) with three features each. Assume that only one aircraft type uses each feature and that each feature on one airfield is identical to its counterpart on the other airfield. The input data of traffic percentages, traffic volume, and PCI are given below.

Feature	Aircraft	Edge Stress	Modulus of Rupture of Concrete	Percentage of Aircraft Using Feature at Airfield	PCI
A1	F4	470 psi	750 psi	15	80
A2	F4	470 psi	750 psi	35	50
A3	F4	470 psi	750 psi	50	30
B1	F4	470 psi	750 psi	25	60
B2	F4	470 psi	750 psi	45	30
B3	F4	470 psi	750 psi	30	53

TABLE 17. STATISTICS FOR THE PCC AND AC/PCC PCI PREDICTION MODELS DEVELOPED USING LOCALIZED MODELING.

	Model Developed With Data From 12 Bases (Using FY 80 Data)			Model Developed With Data From 1 Base (Using FY 80 Data)		
	R^2	Std. Dev.	No. Cases	R^2	Std. Dev.	No. Cases
Universal Model (12 AFB)	.740	8.12	318	--	--	--
Dover AFB	.640	8.55	32	.749	7.67	32
Robins AFB	.828	5.92	56	.917	4.19	56

Airfield	Recorded Absolute Number of Operations per year	Years of Operation
A	100,000	15
B	50,000	15

The following fatigue variable (FAT1) is used in the example:

$$FAT1 = \frac{VAR1 \times VAR2 \times VAR3 \times (.75 \times VAR4)}{VAR5}$$

where:

VAR1 = base operations per year
VAR2 = number of years of operation
VAR3 = percentage of aircraft that use the given feature divided by 100
VAR4 = edge stress created by aircraft
VAR5 = modulus of rupture of concrete

For feature A1, $FAT1 = \frac{(100,000) \times (15) \times (.15) \times (.75 \times 470)}{750} = 105,750$

Feature	FAT1	PCI
A1	105,750	80
A2	246,750	50
A3	362,500	30
B1	88,125	60
B2	158,625	30
B3	105,750	53

There is a good correlation between FAT1 and PCI when only one airfield is considered, but it is not as good as when all the features are combined. Within a given base, changing the absolute number of operations will not affect the correlation for that base. If the base civil engineer knew the approximate percentage of aircraft using a feature, but not the actual volume, the correlation between FAT1 and PCI would not change. In most cases, the actual traffic volume was probably inaccurate. Thus, localized modeling is the only solution to the problem of inconsistent traffic data.

Another reason for favoring localized modeling is that at a given base, construction methods, maintenance procedures and policies, and environmental and drainage conditions are relatively uniform. In the universal models which were developed, the differences in construction methods, maintenance, procedures, environmental and drainage conditions from base to base were usually not fully accounted for.

Thus, the concept of local modeling appears to be impressive and should be investigated further.

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS

Extensive data were collected from 327 airfield pavement features at 12 U.S Air Force bases. The data, which provided a wide range of information on designs, materials, traffic, and climate, were used to develop PCI and key distress prediction models for both asphalt and concrete pavements. Several models were developed for predicting many types of pavement distresses as well as the PCI. Only four of these models provided satisfactory prediction reliability:

1. PCI for PCC and AC/PCC pavements

2. PCI for AC and AC/AC pavements

3. Corner breaks in PCC pavements

4. Reflection cracking in AC/PCC pavements.

Additional data were collected from five Air Force bases for 101 features that had been surveyed previously. These data were used to further evaluate the four prediction models thought to be reliable. The evaluation showed that the PCI prediction models are satisfactory. The reflection cracking model also provided reasonable prediction of eight pavement features (Section VI, Figure 96), which is adequate to show its reliability. However, verification of the corner break model showed that it was not satisfactory (Section VI, Figure 94).

Evaluation of the models for each of the five bases showed that predictions for some of the bases were much better than others, possibly because some of the material properties, climatic factors, and traffic conditions in certain bases were not well represented in the overall model. Thus, it was concluded that localized modeling could provide much more accurate predictions.

1. Climate data will be the same for all features at one base, therefore need not be included in the localized model.

2. Errors in traffic surveys are likely to be more uniform within a single base, thus minimizing prediction errors.

3. The subgrade conditions are likely to be less variable, thus minimizing the errors resulting from inadequate modeling of foundation support.

Furthermore, the concept of localized modeling offers the extra advantage of updating the models as more condition surveys are performed. Based on these results, the following recommendations are made:

1. The PCI prediction models for PCC and AC/PCC, and for AC and AC/AC are recommended for use when projecting network conditions.

2. The distress prediction models should not be implemented.

3. The concept of localized modeling is strongly recommended for development, since it has much potential for providing better predictions.

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APPENDIX A

DATA COLLECTION SHEETS AND CODE SHEETS

DEVELOPMENT OF A PAVEMENT

MAINTENANCE MANAGEMENT SYSTEM

DATA COLLECTION SHEETS

Name of Person Filling out Sheets______________________________

Name of Firm Employing this Person______________________________

Date______________________________

RETURN TO: USA/CERL (Dr. M. Shahin)
P.O. Box 4005
Champaign, IL 61820

PHONE: Commercial - (217) 352-6511
Autovon - 862-1110, then ask for CERL

GENERAL INSTRUCTIONS

This set of data collection sheets will be used in the development of maintenance and repair consequence prediction equations. To be successful and guaranteed of meaningful results, these sheets must be filled out as accurately and completely as possible. To insure uniform results and complete data collection, the following guidelines are to be followed.

1. Record information in the data boxes provided noting the location of the decimal point. (One letter or number in each box.)
2. If actual data are not available (e.g., concrete modulus of rupture data is missing and not known) record an estimate of data in the data boxes and write EST to the left of the data boxes. It is very important that all missing data be estimated based on the best available information.
3. If data are not applicable (e.g., concrete modulus of rupture for an asphalt pavement) record N/A across the data boxes.

Data boxes will be filled with real or coded values. The real values are used for quantifiable variables such as lengths and widths of pavement features, thickness of pavement layers, and strength of materials. Coded values are used for variables that are not quantifiable. Accompanying these field sheets is a set of code sheets. When the field sheet variable is followed by a +, this means that the value of the variable is to be determined as per instructions in the code sheets. The order in which variables are presented in the code sheets is the same as in the field sheets. It is requested that the code sheets be followed through step by step with the field sheets to guarantee uniform results.

I. Feature Identification

1. Air Force Major Command+ ☐☐ 1 2

2. Air Force Base+ ☐☐☐ 3 4 5

3. Existing Feature Type+ ☐ 6

4. Feature Identification Number+ ☐☐☐ 7 8 9

(Actual Base Feature Designation_________)

(Date of Pavement Evaluation Report Used_______________)

5. Length of Feature (Ft.) (If Applicable) ☐☐☐☐☐ 10 11 12 13 14

6. Width of Feature (Ft.) (If Applicable) ☐☐☐☐ 15 16 17 18

7. Area of Feature (Ft.^{2}) ☐☐☐☐☐☐☐☐ 19 20 21 22 23 24 25 26

8. Original or Duplicated Data

(Blank/27-39)

II. Pavement Layer Information ☐ 40

3rd Overlay
2nd Overlay
1st Overlay
Original Surface
Base
Subbase #1
Subbase #2
Subbase #3
Subgrade

1. Type of Existing Pavement+ ☐☐ 41 42

(Specify if other____)

+See Code Sheets for Numbering Code

2. 3rd Overlay

A. Date of Placement (yr) — 43 44

B. Material Type† — 45 46

(Specify if other ____________________)

C. Thickness (inches) — 47 48 49

D. Modulus of Rupture (psi) — 50 51 52

E. Bond Type† (for concrete overlay only) — 53

F. Asphalt Properties

.1 Date of Testing (yr) — 54 55

.2 % Asphalt — 56 57

.3 Air Voids% — 58 59 60

.4 Voids Filled% — 61 62 63

.5 Marshall Stability (lbs) — 64 65 66 67

.6 Flow (0.01 inches) — 68 69

.7 Penetration (mm x 10^{-1}) — 70 71 72

73 74 75 76 77 78 79 80

4. 1st Overlay

A. Date of Placement (yr) — 41 42

B. Material Type† — 43 44

(Specify if other ____________________)

C. Thickness (inches) — 45 46 47

D. Modulus of Rupture (psi) — 48 49 50

E. Bond Type† (for concrete pavement only) — 51

F. Asphalt Properties

.1 Date of Testing (yr) — 52 53

.2 % Asphalt — 54 55

.3 Air Voids (%) — 56 57 58

.4 Voids Filled (%) — 59 60 61

.5 Marshall Stability (lbs) — 62 63 64 65

.6 Flow (0.01 inches) — 66 67

.7 Penetration (mm x 10^{-1}) — 68 69 70

(Blank/71-72)

73 74 75 76 77 78 79 80

5. Original or Reconstructed Surface

A. Date of Placement (yr) — 1 2

B. Material Type+ — 3 4

(Specify if other ______________________________)

C. Thickness (inches) — 5 6 7

D. Modulus of Rupture (psi) — 8 9 10

E. Asphalt Properties

.1 Date of Testing (yr) — 11 12

.2 % Asphalt — 13 14

.3 Air Voids (%) — 15 16 17

.4 Voids Filled (%) — 18 19 20

.5 Marshall Stability (lbs) — 21 22 23 24

.6 Flow (0.01 inches) — 25 26

.7 Penetration (mm x 10^{-1}) — 27 28 29

(Blank/30 - 40)

6. Base Layer

A. Date of Placement (yr) [ ][ ] 41 42

B. Material Type+ [ ][ ] 43 44

(Specify if other ______________________________)

C. Thickness (inches) [ ][ ].[ ] 45 46 47

D. K-Value (pci at top of base layer) [ ][ ][ ] 48 49 50

E. K_f+value (for frost melting period) [ ][ ][ ] 51 52 53

F. Modulus of Rupture (psi) [ ][ ][ ] 54 55 56

G. CBR (%) [ ][ ][ ] 57 58 59

H. Marshall Stability (lbs) [ ][ ][ ][ ] 60 61 62 63

I. Insitu Dry Density (% of optimum) [ ][ ][ ].[ ] 64 65 66 67

J. Insitu Moisture Content (%) [ ][ ].[ ] 68 69 70

(Blank/71 - 72)

[ ][ ][ ][ ][ ][ ][ ][ ] 73 74 75 76 77 78 79 80

7. Subbase Layer #1

A. Date of Placement (yr) — 1 2

B. Material+ — 3 4

(Specify if other________________________________)

C. Thickness (inches) — 5 6 7

D. CBR (%) — 8 9 10

E. Insitu Dry Density (% of optimum) — 11 12 13 14

R. Insitu Moisture Content (%) — 15 16 17

(Blank/18 - 25)

8. Subbase Layer #2

A. Date of Placement (yr) — 26 27

B. Material+ — 28 29

(Specify if other________________________________)

C. Thickness (inches) — 30 31 32

D. CBR (%) — 33 34 35

E. Insitu Dry Density (% of optimum) — 36 37 38 39

F. Insitu Moisture Content (%) — 40 41 42

(Blank/43 - 50)

9. Subbase Layer #3

   A. Date of Placement (yr) — 51 52

   B. Material Type+ — 53 54

      (Specify if other____________________)

   C. Thickness (inches) — 55 56 57

   D. CBR (%) — 58 59 60

   E. Insitu Dry Density (% of optimun) — 61 62 63 64

   F. Insitu Moisture Content (%) — 65 66 67

(Blank/68 - 72)

10. Joint Design — 73 74 75 76 77 78 79 80

   A. Slab Length (Ft) — 1 2 3

   B. Slab Width (Ft) — 4 5 6

   C. Longitudinal Joint Design+ — .1 PAVING LANE — 7

      (Specify if other____________________)

      .2 INTERMEDIATE — 8

   D. Transverse Joint Design+ — 9

      (Specify if other____________________)

   E. Original Joint Filler — 10

      (Specify if other____________________)

(Blank/11 - 15)

III. Foundation (Subgrade) Information*

1. Modifier Applied to Subgrade† ☐ 16

   (Specify if other________________________________)

2. Unified Classification Index of Final In Place Soil*† ☐☐ 17 18

3. CBR (%) ☐☐☐ 19 20 21

4. K-value (pci on top of subgrade) ☐☐☐ 22 23 24

5. Plasticity Index ☐☐ 25 26

6. Liquid Limit ☐☐ 27 28

7. Optimum Moisture Content (C. E. 55) ☐☐☐ 29 30 31

8. Insitu Moisture Content (%) ☐☐☐ 32 33 34

9. Insitu Dry Density (% of optimun) ☐☐☐☐ 35 36 37 38

10. Depth of Water Table† (ft. below pavement surface) ☐☐☐ 39 40 41

*If the soil (subgrade) has been modified in any way, the properties of soil classification, CBR, K, Plasticity Index, Optimum Moisture Content, and Actual Moisture Content are to be measures of the modified soil.

IV. Traffic

1. Present Mission

A. Dates From (yr) [ ][ ] 42 43

To (present) [ ][ ] 44 45

B. Feature Type† [ ] 46

C. Traffic Area† [ ] 47

D. Primary or Secondary [ ] 48

E. Traffic Characteristics for Feature*

	Typical Aircraft	Percent of all Categories
Category #1	________________	[ ][ ][ ] 49 50 51
Category #2	________________	[ ][ ][ ] 52 53 54
Category #3	________________	[ ][ ][ ] 55 56 57
Category #4	________________	[ ][ ][ ] 58 59 60
Category #5	________________	[ ][ ][ ] 61 62 63
Category #6	________________	[ ][ ][ ] 64 65 66

F. Average Annual Operations of Feature (All Aircraft) ________ [ ][ ][ ][ ][ ][ ] 67 68 69 70 71 72

*Traffic characteristics and composition is one of the most difficult items to pinpoint and define. To insure uniformity in data collection, please be sure to read instructions prefacing these field sheets. Instructions and example are also in code sheets.

[ ][ ][ ][ ][ ][ ][ ][ ] 73 74 75 76 77 78 79 80

IV. Traffic

2. First Previous Mission

A. Dates From (yr) [ ][ ] 1 2

To (yr) [ ][ ] 3 4

B. Feature Type† [ ] 5

C. Traffic Area† [ ] 6

D. Primary or Secondary [ ] 7

E. Traffic Characteristics for Feature*

	Typical Aircraft	Percent of all Categories
Category #1	____________	[ ][ ][ ] 8 9 10
Category #2	____________	[ ][ ][ ] 11 12 13
Category #3	____________	[ ][ ][ ] 14 15 16
Category #4	____________	[ ][ ][ ] 17 18 19
Category #5	____________	[ ][ ][ ] 20 21 22
Category #6	____________	[ ][ ][ ] 23 24 25

F. Average Annual Operations of Feature (All Aircraft) ____________ [ ][ ][ ][ ][ ] 26 27 28 29 30

*See note on page 10.

IV. Traffic

3. Second Previous Mission

A. Dates From (yr) [ ][ ] 31 32

To (yr) [ ][ ] 33 34

B. Feature Type† [ ] 35

C. Traffic Area† [ ] 36

D. Primary or Secondary† [ ] 37

E. Traffic Characteristics for Feature*

	Typical Aircraft	Percent of all Categories
Category #1	____________	[ ][ ][ ] 38 39 40
Category #2	____________	[ ][ ][ ] 41 42 43
Category #3	____________	[ ][ ][ ] 44 45 46
Category #4	____________	[ ][ ][ ] 47 48 49
Category #5	____________	[ ][ ][ ] 50 51 52
Category #6	____________	[ ][ ][ ] 53 54 55

F. Average Annual Operations of Feature ____________ [ ][ ][ ][ ][ ] 56 57 58 59 60
(All Aircraft)

*See note on page 10.

V. Maintenance

1. Crack Filling† — 61

2. Joint/Crack Filling Interval† (Average time in yrs between joint/crack filling - see code sheets for example)† — 62 63

3. Slab Replacement†

   A. % of Total Area — 64 65

   B. Average Age (yrs) — 66 67 68

4. Surface Sealcoat Not Containing Aggregate* (Mean time in years between sealcoats; e.g., fog, rejuvenator) — 69 70

5. Surface Treatment Containing Aggregate* (Mean time in years between surface treatments, e.g., slurry, aggregate seal) — 71 72

VI. PCI & Distress Information — 73 74 75 76 77 78 79 80

   A. PCI — 1 2 3

   B. Date PCI Determined (Month, Year)** — 4 5 6 7

   C. Standard Deviation — 8 9 10

   D. Total Number of Sample Units in Feature — 11 12 13

   E. Number of Random Sample Units Surveyed — 14 15 16

   F. Number of Additional Sample Units Surveyed — 17 18

   G. Adequate Number of Units Sampled? — 19

*Compute the Same as Joint Filling

**First 2 boxes are for the month (i.e. Jan=01, Feb=02, March=03...) Second 2 boxes are for the year (i.e. 1979=79, 1981=81)

(Blank/20-24)

DISTRESS DATA* Field Sheets - Page 14

(Enter distress density per feature)

ASPHALT/CONCRETE	LOW SEV.	MED. SEV.	HIGH SEV.
1. Alligator/Blow Up	25 26 27 28	29 30 31 32	33 34 35 36
2. Bleeding/Corner Break	37 38 39 40	41 42 43 44	45 46 47 48
3. Block Cracking/Longitudinal, Transverse and Diagonal Cracks	49 50 51 52	53 54 55 56	57 58 59 60
4. Corrugation/Durability ("D") Cracking	61 62 63 64	65 66 67 68	69 70 71 72
5. Depression/Joint Seal Damage 73 74 75 76 77 78 79 80	1 2 3 4	5 6 7 8	9 10 11 12
6. Jet Blast Erosion/Small Patching	13 14 15 16	17 18 19 20	21 22 23 24
7. Joint Reflection Cracking/Large Patching	25 26 27 28	29 30 31 32	33 34 35 36
8. Longitudinal and Transverse Cracking/Popouts	37 38 39 40	41 42 43 44	45 46 47 48
9. Oil Spillage/Pumping	49 50 51 52	53 54 55 56	57 58 59 60
10. Patching/Scaling, Map Cracking, and Crazing	61 62 63 64	65 66 67 68	69 70 71 72
11. Polished Aggregate/Settlement or Faulting 73 74 75 76 77 78 79 80	1 2 3 4	5 6 7 8	9 10 11 12
12. Raveling and Weathering/Shattered Slab, Intersecting Cracks	13 14 15 16	17 18 19 20	21 22 23 24
13. Rutting/Shrinkage Cracks	25 26 27 28	29 30 31 32	33 34 35 36
14. Shoving/Spalling (Transverse and Longitudinal Joint)	37 38 39 40	41 42 43 44	45 46 47 48
15. Slippage/Spalling (Corner)	49 50 51 52	53 54 55 56	57 58 59 60
16. Swell/	61 62 63 64	65 66 67 68	69 70 71 72

*For distress data, results from the PCI computer program should be used. Values are in percentages of the total feature affected. In cases where 100% of feature is affected, record 99.99 in the boxes. Distress types with no specified severity level should be recorded in the low severity column. i.e., Swell

73 74 75 76 77 78 79 80

US AIR FORCE BASES

AIR BASE	CODE	AIR BASE	CODE
ALTUS AFB, OK	001	ELLSWORTH AFB, SD	024
ANDREWS AFB, MD	002	ELMENDORF AFB, AK	025
BARKSDALE AFB, LA	003	ENGLAND AFB, LA	026
BEALE AFB, CA	004	FAIRCHILD AFB, WA	027
BERGSTROM AFB, TX	005	F E WARREN AFB, WY	028
BLYTHEVILLE AFB, AR	006	GEORGE AFB, CA	029
CANNON AFB, NM	007	GRAND FORKS AFB, ND	030
CAPE CANAVERAL AFB, FL	008	GREATER PITTSBURGH IAP, PA	031
CARSWELL AFB, TX	009	GRIFFISS AFB, NY	032
CASTLE AFB, CA	010	GRISSOM AFB, IN	033
CHANUTE AFB, IL	011	HANCOCK FLD, NY	034
CHARLESTON AFB, SC	012	HICKMAN AFB, HI	035
CHICAGO O'HARE IAP, IL	013	HILL AFB, NM	036
COLUMBUS AFB, MS	014	HOLLOMAN AFB, NM	037
DAVIS-MONTHAN AFB, AZ	015	HOMESTEAD AFB, FL	038
DOBBINS AFB, GA	016	KEESLER AFB, MS	039
DOVER AFB, DE	017	KELLY AFB, TX	040
DULUTH IAP, MN	018	KINCHELOE AFB, MI	041
DYESS AFB, TX	019	KIRTLAND AFB, NM	042
EDWARDS AFB, CA	020	K I SAWYER AFB, MI	043
EGLIN AFB, FL	021	LANGLEY AFB, VA	044
EIELSON AFB, NORTH POLE	022	LAUGHLIN AFB, TX	045
ELLINGTON AFB, TX	023	L G HANSCOM AFB, MA	046

AIR BASE	CODE	AIR BASE	CODE
LITTLE ROCK AFB, AR	047	RANDOLPH AFB, TX	073
LORING AFB, ME	048	REESE AFB, TX	074
LOS ANGELES AFS, CA	049	RICHARDS-GEBAUR AFB, MO	075
LUKE AFB, AZ	050	RICKENBACKER AFB, OH	076
MACDILL AFB, FL	051	ROBINS AFB, GA	077
MALMSTROM AFB, MT	052	SCOTT AFB, IL	078
MARCH AFB, CA	053	SELFRIDGE ANG BASE, MI	079
MATHER AFB, CA	054	SEYMOUR JOHNSON AFB, NC	080
MAXWELL AFB, AL	055	SHAW AFB, SC	081
MCCHORD AFB, WA	056	SHEPPARD AFB, TX	082
MCCLELLAN AFB, CA	057	TINKER AFB, OK	083
MCCONNELL AFB, KS	058	TRAVIS AFB, CA	084
MCGUIRE AFB, NJ	059	TYNDALL AFB, FL	085
MINNEAPOLIS-ST PAUL IAP, MN	060	VANDENBERG AFB, CA	086
MINOT AFB, ND	061	WESTOVER AFB, MA	087
MOODY AFB, GA	062	WHITEMAND AFB, MO	088
MT HOME AFB, ID	063	WILLIAMS AFB, AZ	089
MYRTLE BEACH AFB, SC	064	WILLOW GROVE NAS, PA	090
NELLIS AFB, NV	065	WRIGHT-PATTERSON AFB, OH	091
NORTON AFB, CA	066	WURTSMITH AFB, MI	092
OFFUTT AFB, NE	067	YOUNGSTOWN MUNI APRT, OH	093
PATRICK AFB, FL	068	OVERSEAS U.S. AIR FORCE BASES	
PEASE AFB, NH	069	ACENSION AFB (AFSC), PI	200
PETERSON AFB, CO	070	ANDERSEN AFB, GU	201
PLATTSGURGH AFB, NY	071	AVIANO AB, IT	202
POPE AFB, NC	072	BITBURG AB, GE	203

AIR BASE	CODE
CAMP NEW AMSTERDAM AB, NETHERLANDS	204
CLARK AB, PI	205
HAHN AB, GE	206
HELLENIKON AB, GR	207
HOWARD AFB, CZ	208
INCIRLIK AB, TK	209
KADENA AB, JA	210
KUNSAN AB, KR	211
LAJES FLD, AZORES	212
MISAWA AB, JA	213
MORON AB, SP	214
OSAN AB, KOREA	215
RAF ALCONBURY, UK	216
RAF BENTWATERS, UK	217
RAF FAIRFORD, UK	218
RAF LAKENHEATH, UK	219
RAF MILDENHALL, UK	220
RAF UPPER HEYFORD, UK	221
RAMSTEIN AB, GE	222
RHEIN-MAIN AB, GE	223
SEMBACK AB, GE	224
SPANGDAHLEM AB, GE	225
TACHIKAWA AB, JA	226

AIR BASE	CODE
TORREJON AB, SP	227
YOKOTA AB, JA	228
ZARAGOZA AB, SP	229
ZWEIBRUCKEN AB, GE	230

Pavement Definitions:

PCC: This is a Portland Cement Concrete pavement. It has no overlays and the exposed surface is the original or reconstructed* surface.

PCC/PCC: This is a PCC overlay on top of existing PCC surface course. A PCC overlay with a bond breaking layer between it and the old PCC is also considered PCC/PCC.

PCC/AC: This is a PCC overlay on top of existing AC pavement.

Recycled PCC: Recycled PCC is when the existing surface course was made by removing the old PCC surface, crushing it, and then using it as aggregate in the existing surface course.

AC Sandwich Over PCC: This pavement is defined by covering the old PCC surface course with a bond breaker (usually about 4" granular material) and then resurfacing with AC.

AC: This is an asphalt concrete pavement. It has no overlays and the exposed surface is the original or reconstructed surface.

AC/PCC: This is an AC overlay on top of existing PTC surface course.

AC/AC: This is an AC overlay on top of existing AC surface course. An AC overlay on top of AC sandwich type construction is also considered AC/AC.

Recycled AC: Recycled AC is when the existing surface course was made by removing the old AC surface, crushing it, and then using it as aggregate in the existing surface course.

*Reconstruction is defined as removal and replacement of existing surface and possibly underlying layers, with new materials. The reconstructed surface is considered as the original surface thereafter.

Sandwich Layer Information

Example:

3rd Overlay	
2nd Overlay	
1st Overlay	
Original Surface	3" AC
Base	4" Crushed Stone
Subbase #1	11" PCC
Subbase #2	15" Crushed Stone
Subbase #3	
Subgrade	Lean Clay

Initially 11" PCC was constructed over 15" of crushed stone and a subgrade of lean clay. A bond breaker of 4" crushed stone was then applied over the PCC and a sandwich layer was created when 3" AC was placed on top of the bond breaker. Note that for a sandwich pavement, the sandwich is not recorded as an overlay.

The above diagram illustrates what materials should be listed with what layers for a sandwich.

(2 Thru 9: B) Material Type Code

SURFACE MATERIALS

Material Type	Code
Plain Jointed Concrete	10
Reinforced Jointed Concrete	11
Continuously Reinforced Concrete	12
Prestressed Concrete	13
Fibrous Concrete	14
Asphalt Concrete	15
Road Mix Bituminous Surface	16
Sand-Asphalt	17
Single Layer Aggregate Seal Coat	18
Double Layer Aggregate Seal Coat	19
Three or More Layer Aggregate Seal Coat	20
Tar Rubber Concrete	21
Tar Concrete	22
Recycled Asphalt Concrete	23
Other (Specify on Field Sheets)	24

TREATED OR STABILIZED MATERIALS

Material Type	Code
Cement Stabilized	30
Lime-Flyash Stabilized	31
Bituminous Stabilized, Plant Mix	32
Bituminous Stabilized, Road Mix	33
Other (Specify on the Field Sheets)	34

PAVEMENT LAYER INFORMATION (Continued)

MATERIAL TYPE CODE (Continued)

UNTREATED MATERIAL

Material Type	Code
(Unified Soil Classification Index)	
GW	50
GP	51
GW-GM	52
GP-GM	53
GM	54
GM-GC	55
GC	56
SW	57
SP	58
SW-SM	59
SP-SM	60
SM	61
SM-SC	62
SC	63
OL	64
ML	65
ML-CL	66
CL	67
MH	68
OH	69
CH	70
Pt	71

(2 Thru 4: E) Concrete Overlay Bond Type Code

Bond Type	Code
Full Bond	1
Partial Bond	2
No Bond (Bond breaker placed between layers)	3

(6: E) GRAPH FOR K_f Value (See Page 9)

(10: C&D) LONGITUDINAL AND TRANSVERSE JOINT DESIGN CODE (See Page 10 for Diagram)

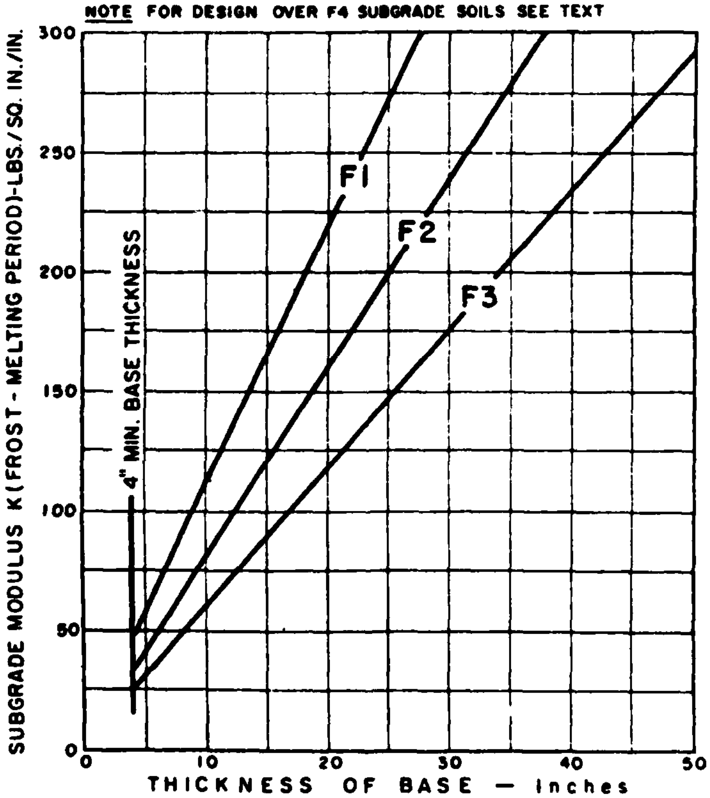
Joint Design	Code
a: Dummy-groove contraction.	1
b: Dummy-groove, doweled, contraction.	2
c: Butt construction	3
d: *Expansion*	4
e: Keyed longitudinal, tied construction	5
f: Keyed hinge or warping construction	6
g: Tied longitudinal warping	7
h: Thickened edge expansion.	8
i: Other	9

(10: E) Original

Joint Filler	Code
Poured Liquid Filler.	1
Preformed Compressed Seal	2
Metal Uni-Tube Insert	3
Other (Specify)	4

GROUP	DESCRIPTION
F1	GRAVELLY SOILS CONTAINING BETWEEN 3 AND 10 PERCENT FINER THAN 0.02 mm BY WEIGHT
F2	(a) GRAVELLY SOILS CONTAINING BETWEEN 10 AND 20 PERCENT FINER THAN 0.02 mm BY WEIGHT (b) SANDS CONTAINING BETWEEN 3 AND 15 PERCENT FINER THAN 0.02 mm BY WEIGHT
F3	(a) GRAVELLY SOILS CONTAINING MORE THAN 20 PERCENT FINER THAN 0.02 mm BY WEIGHT (b) SANDS, EXCEPT VERY FINE SILTY SANDS, CONTAINING MORE THAN 15 PERCENT FINER THAN 0.02 mm BY WEIGHT (c) CLAYS WITH PLASTICITY INDEXES OF MORE THAN 12
F4	(a) ALL SILTS (b) VERY FINE SILTY SANDS CONTAINING MORE THAN 15 PERCENT FINER THAN 0.02 mm BY WEIGHT (c) CLAYS WITH PLASTICITY INDEXES OF LESS THAN 12 (d) VARVED CLAYS AND OTHER FINE-GRAINED BANDED SEDIMENTS.

NOTE FOR DESIGN OVER F4 SUBGRADE SOILS SEE TEXT



FROST CONDITION REDUCED SUBGRADE STRENGTH DESIGN SUBGRADE MODULUS CURVES FOR RIGID AIRFIELD AND HIGHWAY PAVEMENTS

Figure A-1. Graph for Determining Subgrade Modulus at the Frost-Melting Point, K_f (psi/in).

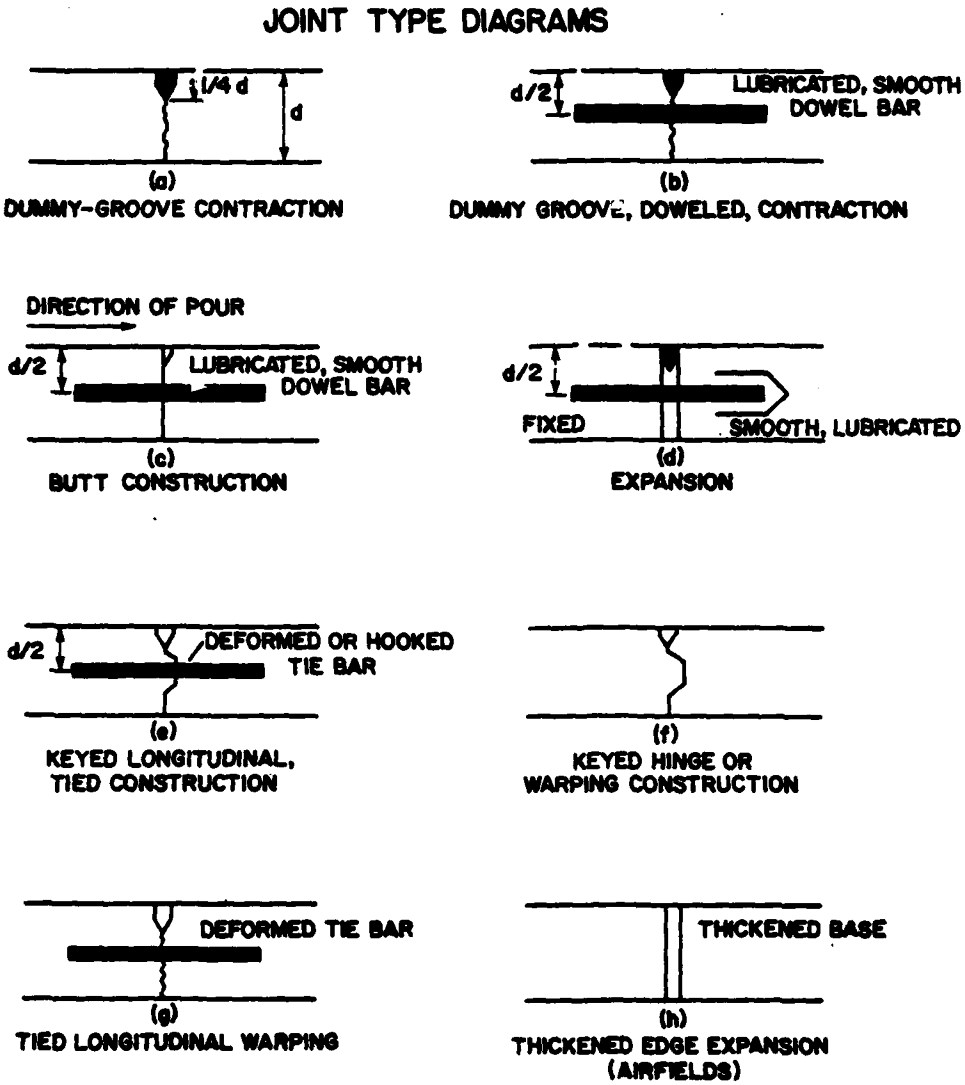


Figure A-2. Longitudinal and Transverse Joint Designs (see page 137 for code).

III. FOUNDATION (SUBGRADE) INFORMATION

1. Soil Modification

	Code
No Modification of Subgrade	1
Bituminous Modification	2
Cement Modification	3
Lime Modification	4
Other (Specify on Field Sheets)	5

2. Soil Classification Index Code - See Material Code Sheet.

IV. TRAFFIC

NOTE: Aircraft are separated into six categories based generally on the relative damage they cause to pavements (as indicated generally by their gross weight and gear configuration). The typical aircraft included in each category are summarized on page 13. If an aircraft that is not listed on page 13 has used the feature, it should be assigned to a category most closely related to its gross take-off weight and gear configuration.

The most representative aircraft using the feature within each category (if any) should be listed in the blank provided (this aircraft will be used for computing stresses and strains for the features). If two or more aircraft within one category are using the feature approximately the same amount, record the aircraft that caused the most damage to the pavement.

The approximate percentage of usage of aircrafts within each category using the feature (with respect to all the categories) during the mission must be determined. For example, a feature could have only T-37 aircraft and thus:

Category 1 T-37 | 1 | 0 | 0 |.

would be recorded on the sheet. All other categories would be filled in with zeros (0). If both T37's and C130's were using a feature, the sheets could be coded as follows:

Category 1	T-37	0 9 0 .
Category 2	--	0 0 0 .
Category 3	C-130	0 1 0 .
Category 4	--	0 0 0 .
etc.		Total = 100.

The total percentage from all categories must equal 100. Additional examples are provided under F. Not all categories need be used if there are none or very few aircraft from those categories actually using the feature.

1. Mission Number

B. Feature Type

	Code
Runway	1
Taxiway	2
Apron	3

C. Traffic Area

Area	Code
A.	1
B.	2
C.	3
D.	4

D. Primary or Secondary

	Code
Primary	1
Secondary	2

F. Traffic Characteristics - Examples

		Typical Aircraft	%
#1	Category #1	T37	47.
	Category #2	F101	38.
	Category #3	---	--
	Category #4	C-141	15.
	Category #5	---	--
	Category #6	---	--
		Total =	100.
#2	Category #1	---	--
	Category #2	F101	5.
	Category #3	F111	5.
	Category #4	---	--
	Category #5	B-52	70.
	Category #6	C-5A	20.
		Total =	100.

AIRCRAFT CATEGORY*

Category	1	2	3	4	5	6
Aircraft Types*	T-33 T-37	A-7 A-10 C-123 F-4 F-5 F-14 F-15 F-16 F-100 F-101 F-102 F-105 F-106 T-29 T-38 T-39	C-7 C-9 C-54 C-119 C-130 C-131 C-140 EC-121 F-111 KC-97 T-43 727 737	C-135 C-141 E-3A KC-135 VC-137 707	B 52	C-5A DC-10 E-4A KC-10A L10-13 747

*Aircraft categories are roughly based on aircraft weight and gear configuration found in "The Theory and Principles of Airfield Pavement Evaluation," James I. Clark, July 1977. Any aircraft not found above, but considered representative of those using the feature, may be put into any one of the six groups corresponding to its weight and gear configuration.

V. MAINTENANCE INDEX CODE

1. Crack Filling

	Code
NONE - General policy not to fill cracks unless an operational hazard exists	1
MINOR - Fill in high severity cracks	2
MODERATE - Fill in medium and high-severity cracks	3
MAJOR - Fill all cracks as they occur and refill as needed	4

2. Joint/Crack Filling

To obtain value, divide the age of the slab by the number of major joint/crack filling projects plus one or, if no filling has been performed, record the age of the slab.

3. Slab Replacement -

$$\% \text{ of Total Area} = \frac{\text{Slabs Replaces}}{\text{Total Number of Slabs}} \times 100$$

Average Age - Since slab replacement may have been done more than once and detailed information on how many were placed at any particular time probably doesn't exist, the average age is an estimate to be made by the base engineer based on when slab replacements were done, i.e., if slab replacement occured 14, 7 and 4 years ago, the average age would be $\frac{14+7+4}{3} = 8.3$ years.

APPENDIX B

DETERMINATION OF MECHANISTIC VARIABLES

A. PCC PAVEMENTS

The maximum free edge stress at the bottom of the concrete slab was selected as the main response parameter for PCC pavement analyses. Charts for 41 different aircraft were prepared to compute the edge stress as a function of the slab thickness and of the modulus of subgrade reaction.

1. Mechanistic Model

The PCC pavement strucure was modeled as a rigid slab resting on an elastic (Winkler-type) foundation. The computerized H-51 procedure (Reference 9) was used to do the computations. This program is a computerized solution of the influence charts for concrete pavements developed by Pickett and Ray (Reference 12).

2. Materials Characterization

A constant E-modulus of 4×10^6 psi was assumed for the PCC slab. Poisson's ratio for the slab was set to 0.15. The modulus of subgrade reaction (K) was read from the field data sheets. The K-value corresponded to the layer material underneath the concrete slab.

3. Aircraft Loading Characterization

Table B-1 summarizes the different aircraft categories used in the PCC pavement analyses. (Charts for stress computations were prepared for those aircraft in Table B-1 marked with a " ** " and presented in this text as Figures B-1 through B-32).

Figure B-33 shows the main gear geometry, gear load, tire contact area, and tire pressure for a B-29 aircraft.

4. Charts for Stress Computations

Figure B-33 shows how the maximum free-edge stress varies with slab thickness for different values of subgrade support. The figure shows the relative orientation of the main gear with respect to the free edge. In all computations, a circular tire imprint was assumed.

5. Procedure Outline

a. For each PCC pavement feature, determine the slab thickness and the modulus of subgrade reaction from the field data sheets.

b. Determine the aircraft types, using the features from the field data sheets.

c. For each aircraft, determine the maximum free-edge stress, using the corresponding chart (Figures B-1 through B-32).

TABLE B-1. AIRCRAFT CATEGORY FOR PCC PAVEMENT ANALYSIS.

Category*	1	2	3	4	5	6
Aircraft Types	T-33**	A-7	C-7	C-135**	B-52**	C-5A**
	F-80**	C-123	C-54**	E-3A		R-5S
		F-4**	C-119	KC-135**		KV-10S
		F-15**	C-130**	VC-137		L-1013
		F-5	C-131**	707**		747**
		F-14	C-140	DC-8A**		
		F-16	EC-121	B-36**		
		F-100	F-111**	C-133		
		F-101	KC-97**	C-141**		
		F-102	T-43	B-47**		
		F-105**	727**			
		F-106	737**			
		T-29**	L-188**			
		T-38**	C-124**			
		T-39**	C-9**			
		F-Series**	DC-9**			
		F-86**	B-29**			
		C-47D**				
		B-17**				
		B-24**				
		B-25**				

*Aircraft categories are roughly based on aircraft weight and gear configuration found in "The Theory and Principles of Airfield Pavement Evaluation," James I. Clark, July 1977. Any aircraft not found above, but considered representative of those using the feature, may be put into any of the six groups corresponding to its weight and gear configuration.

**Charts for stress computations are presented in this report as Figures B-1 through B-32.

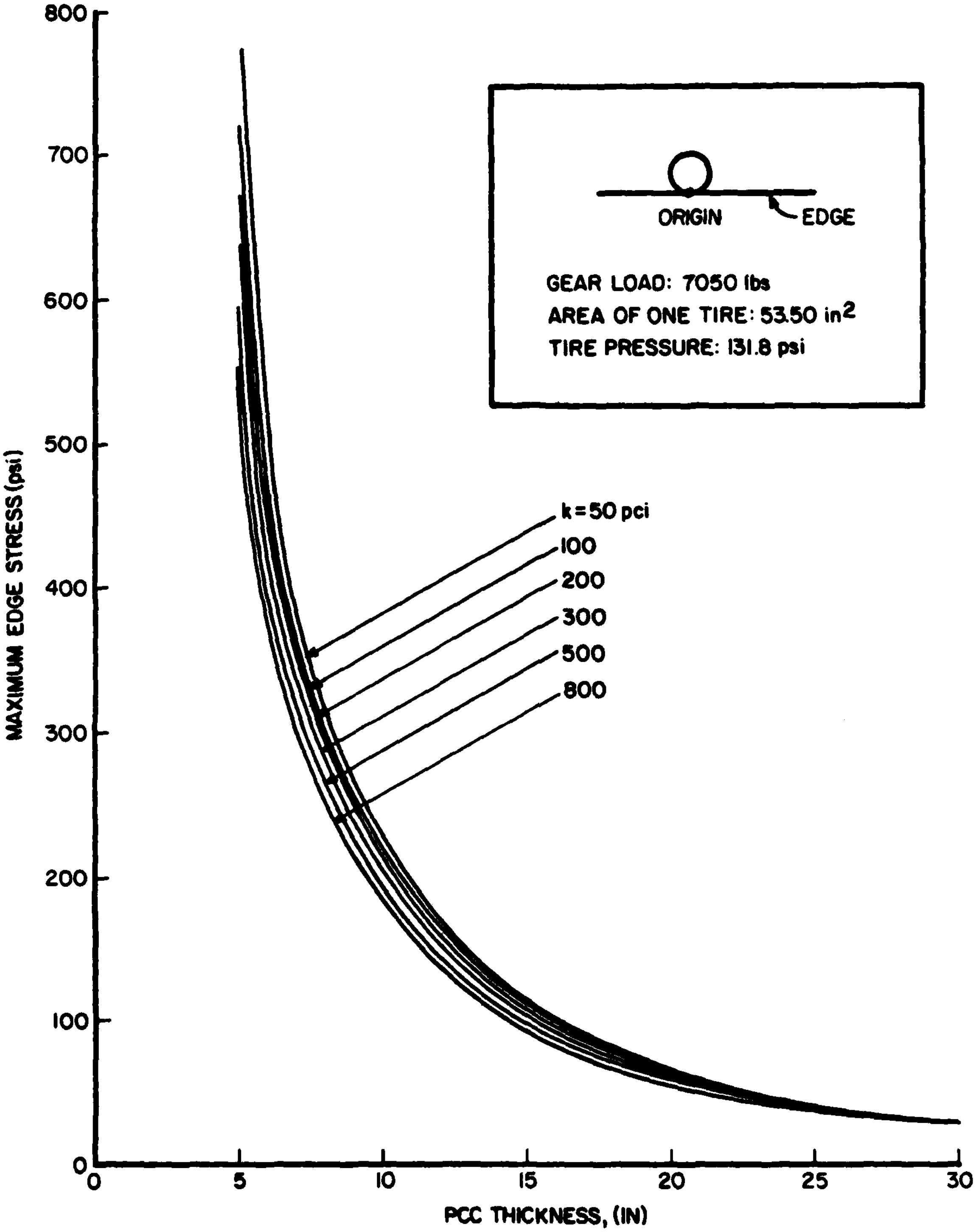


Figure B-1. Stress Chart for T-33 and F-80.

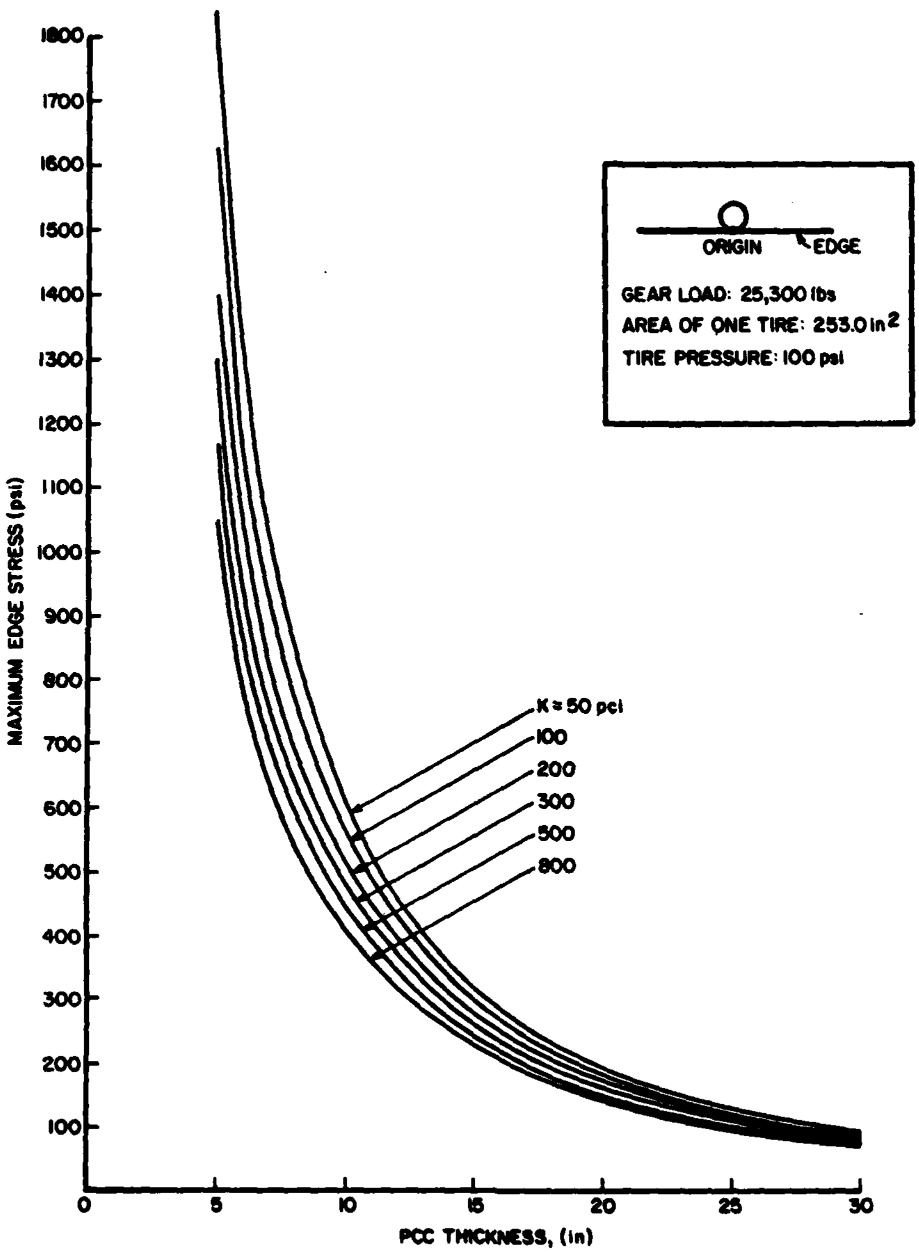


Figure B-2. Stress Chart for C-123.

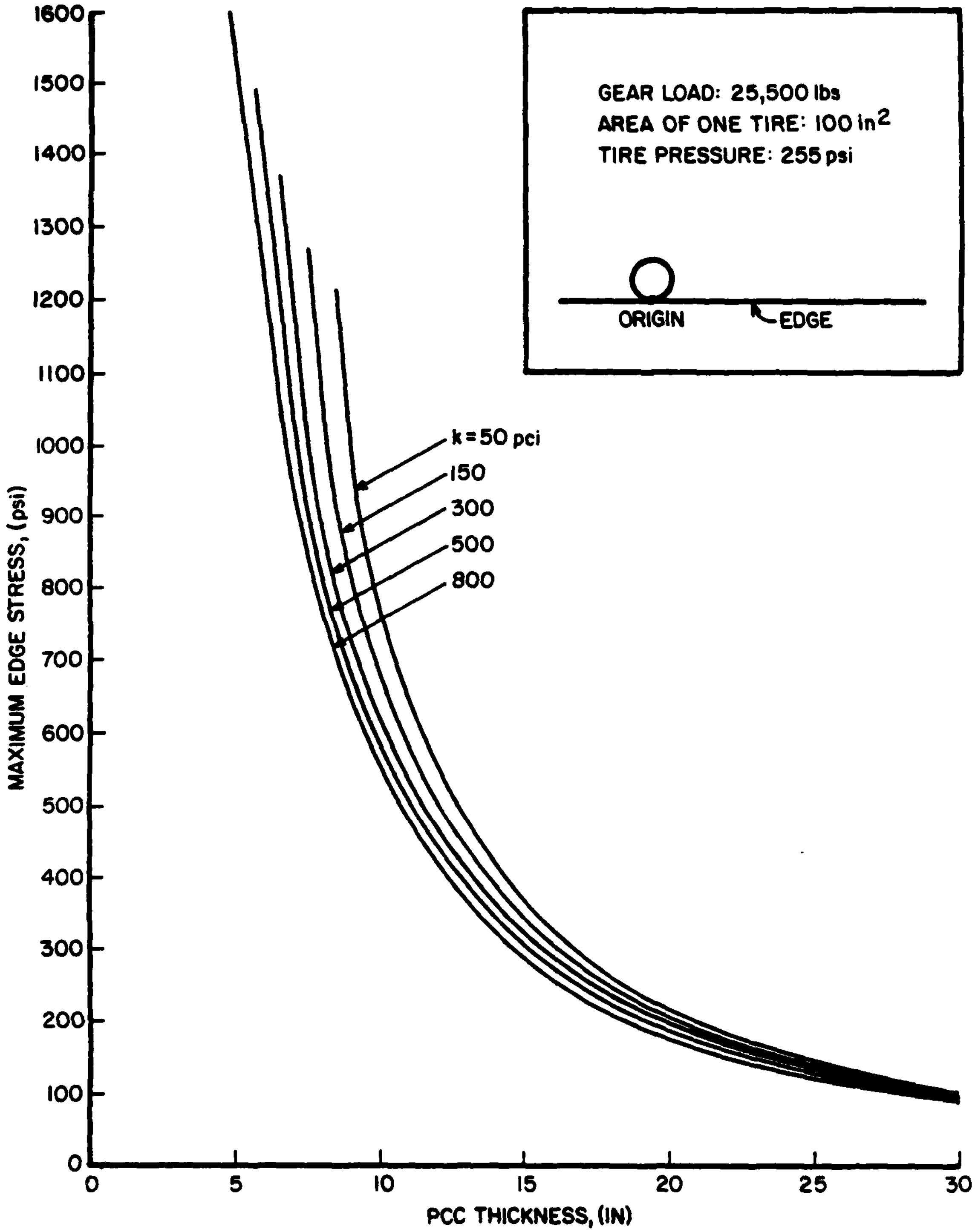


Figure B-3. Stress Chart for F-4 and F-15.

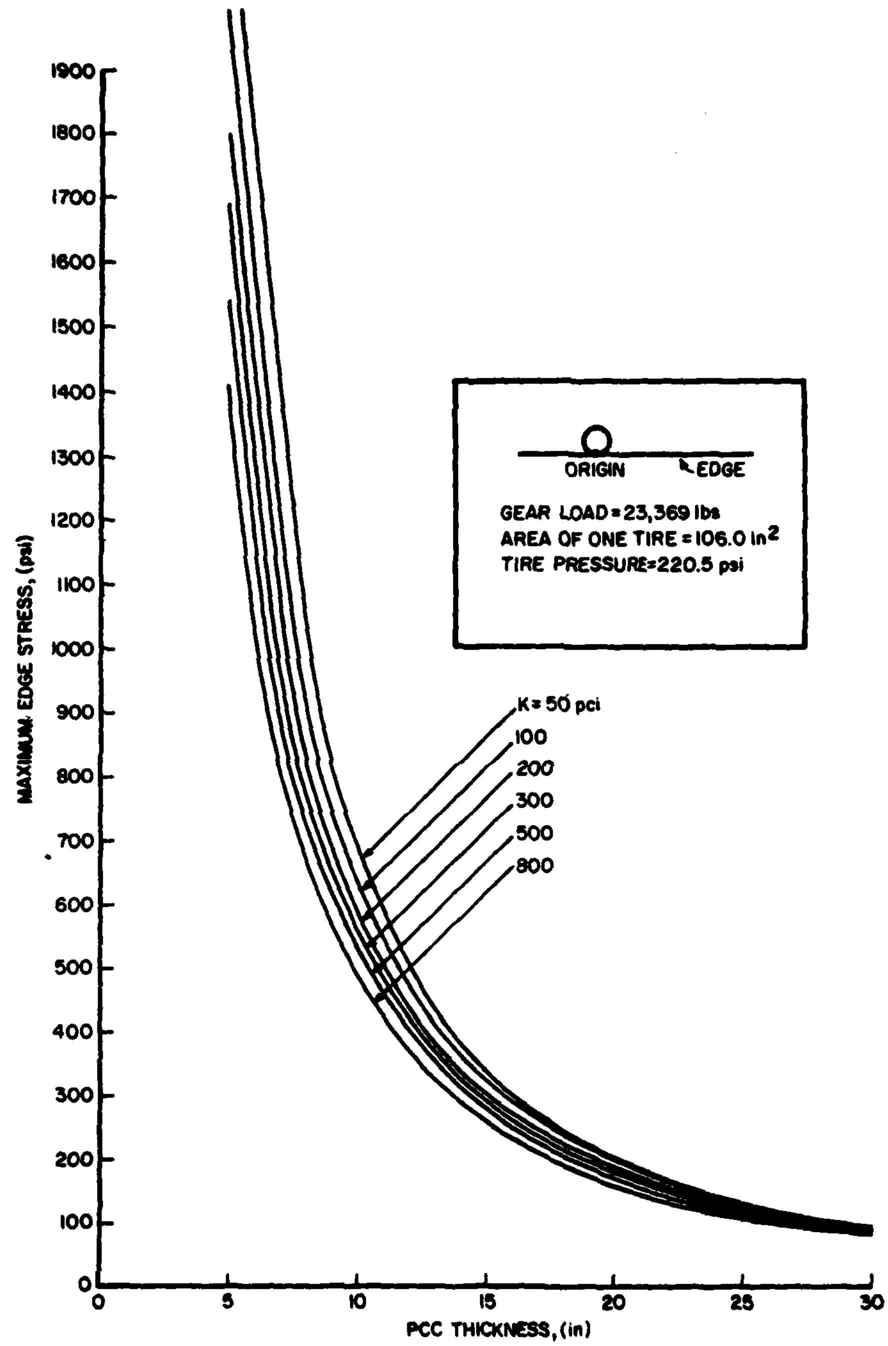


Figure B-4. Stress Chart for F-105.

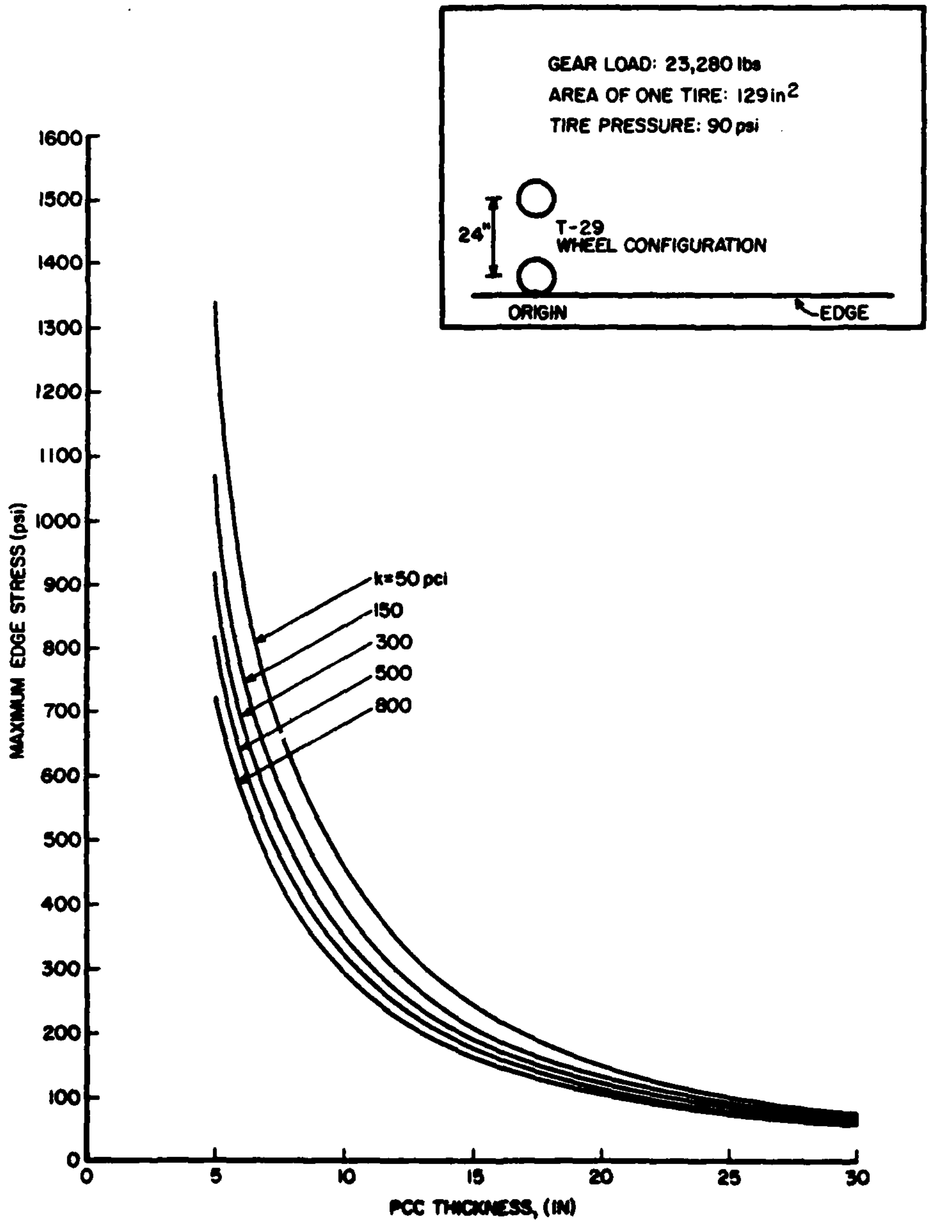


Figure B-5. Stress Chart for T-29.

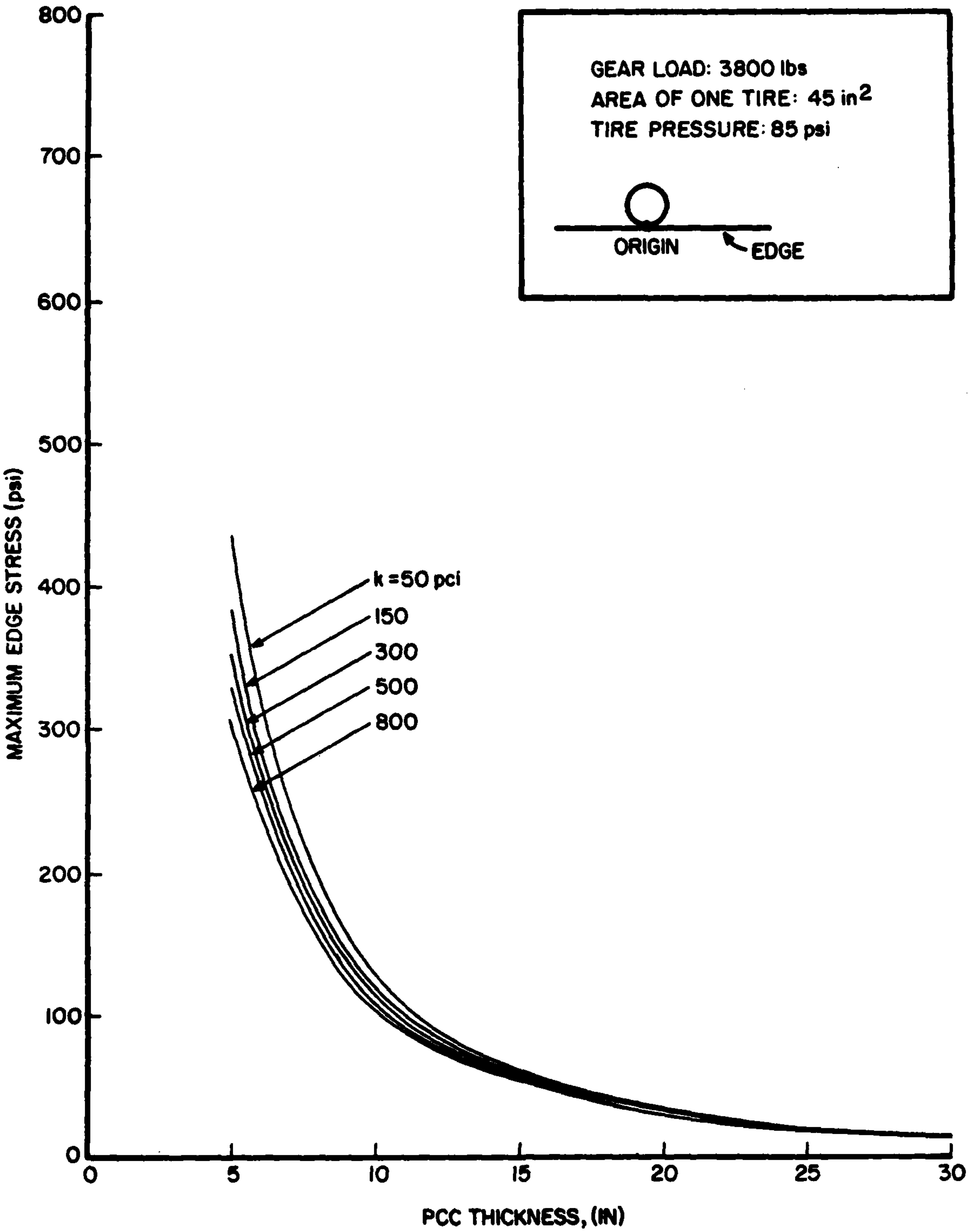


Figure B-6. Stress Chart for T-37.

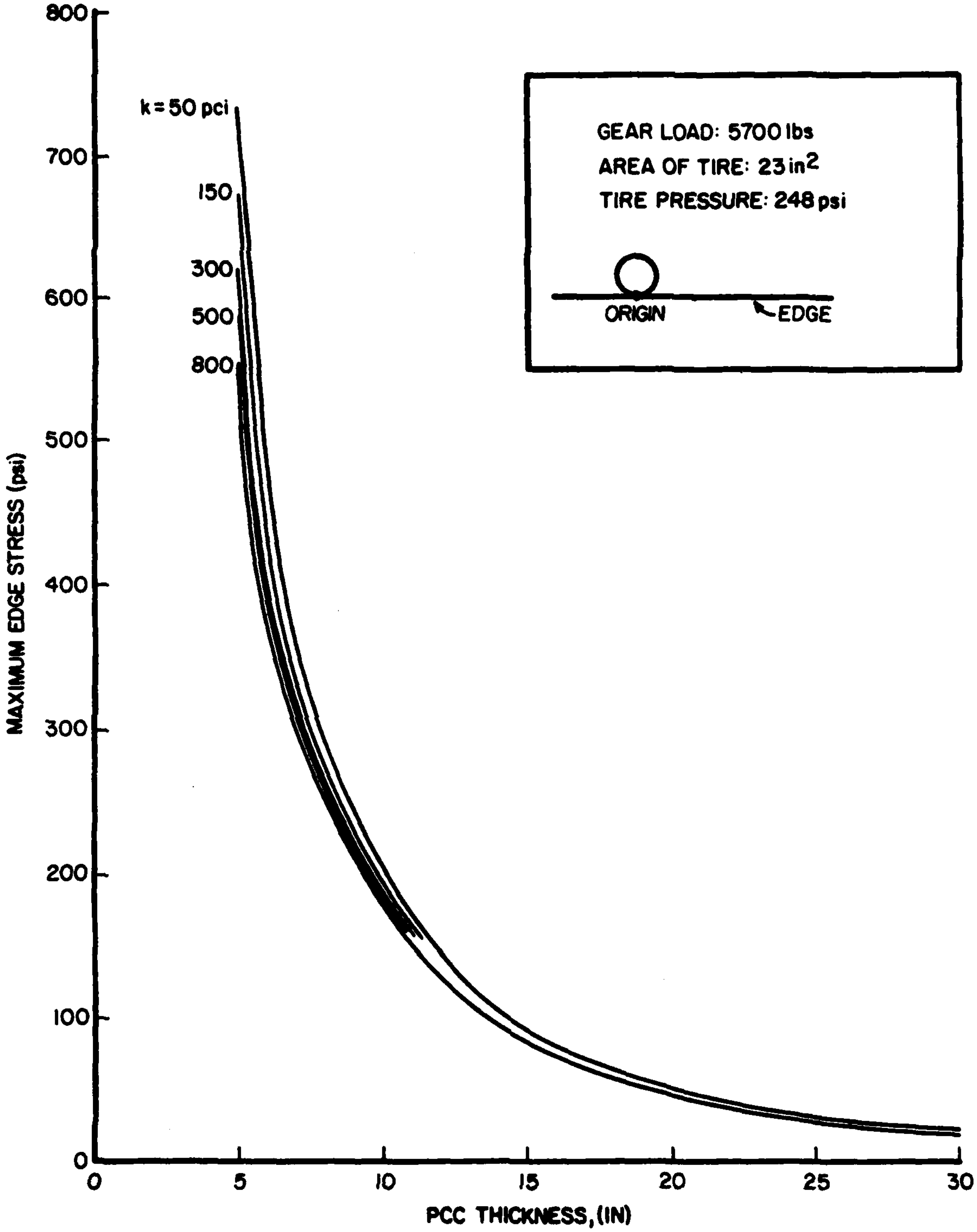


Figure B-7. Stress Chart for T-38.

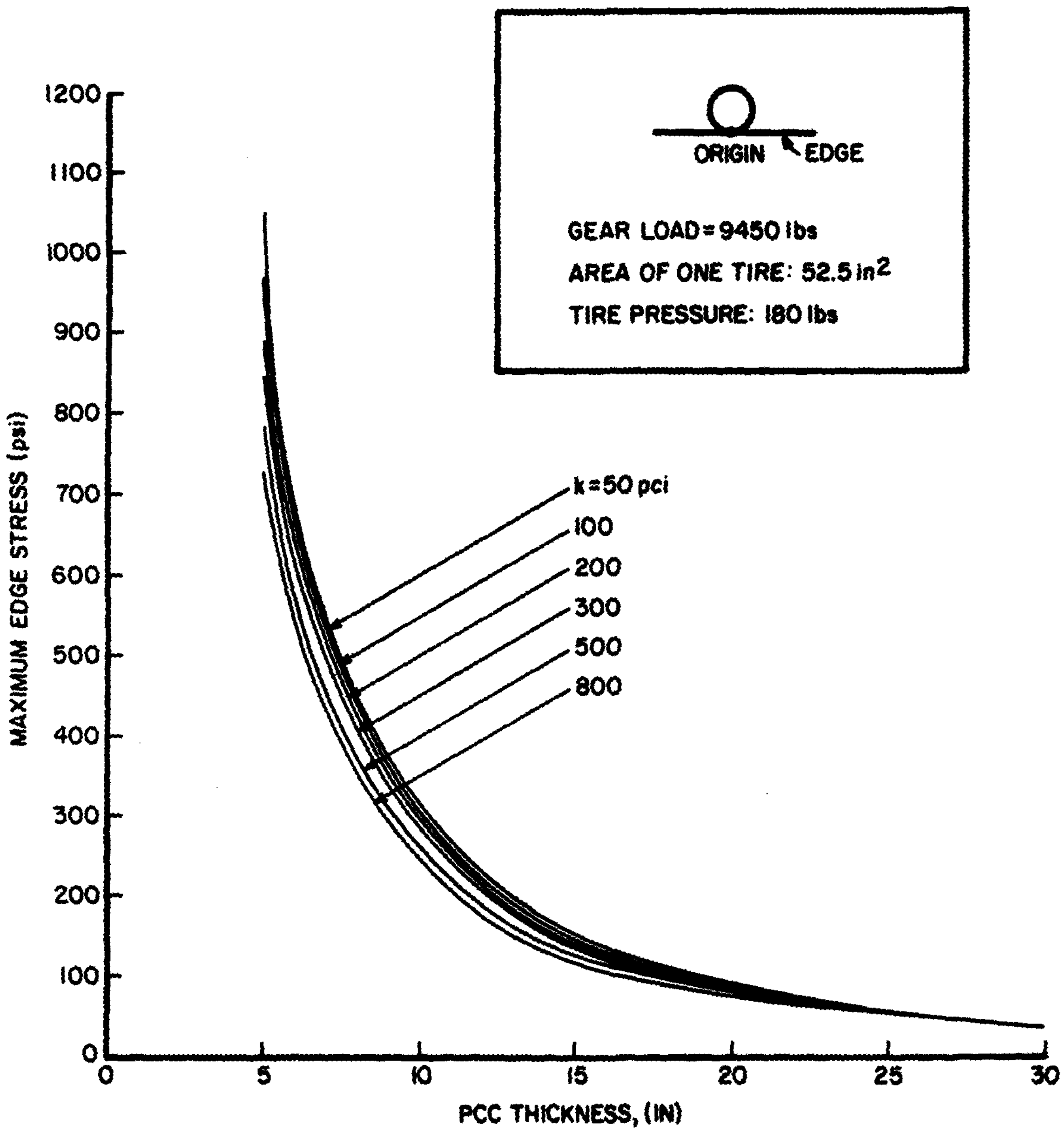


Figure 8-8. Stress Chart for T-39.

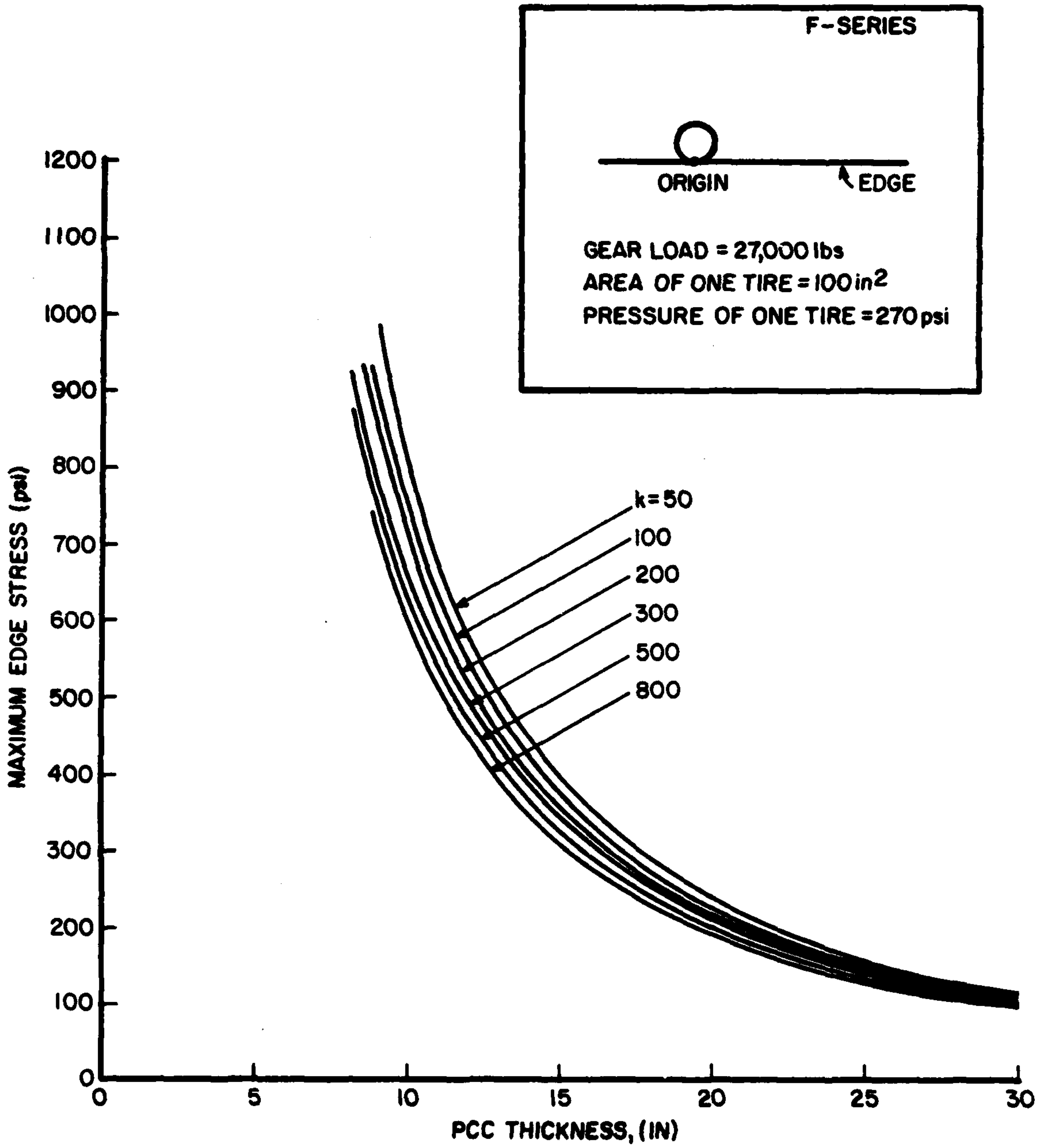


Figure B-9. Stress Chart for F-Series.

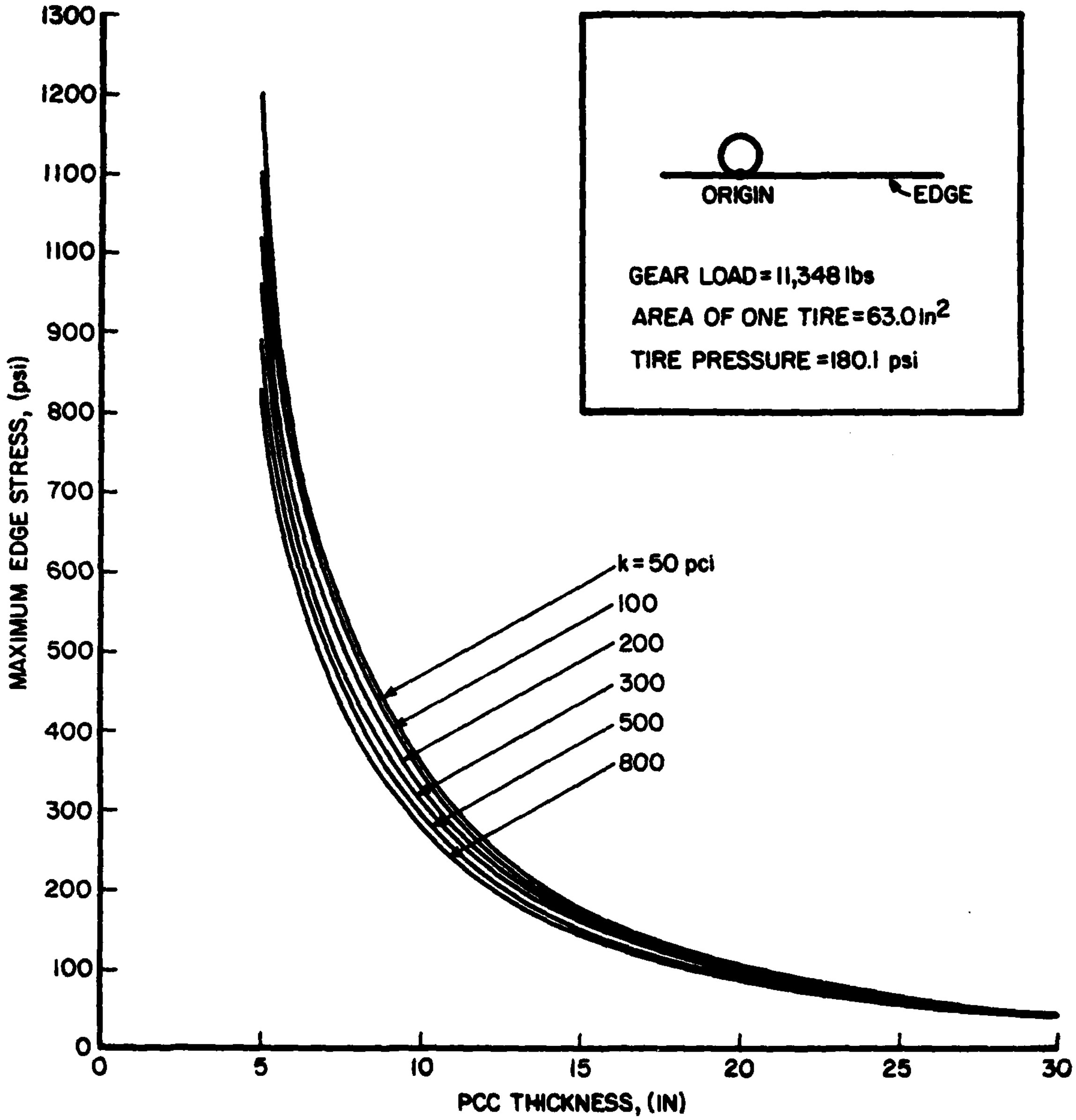


Figure B-10. Stress Chart for F-86.

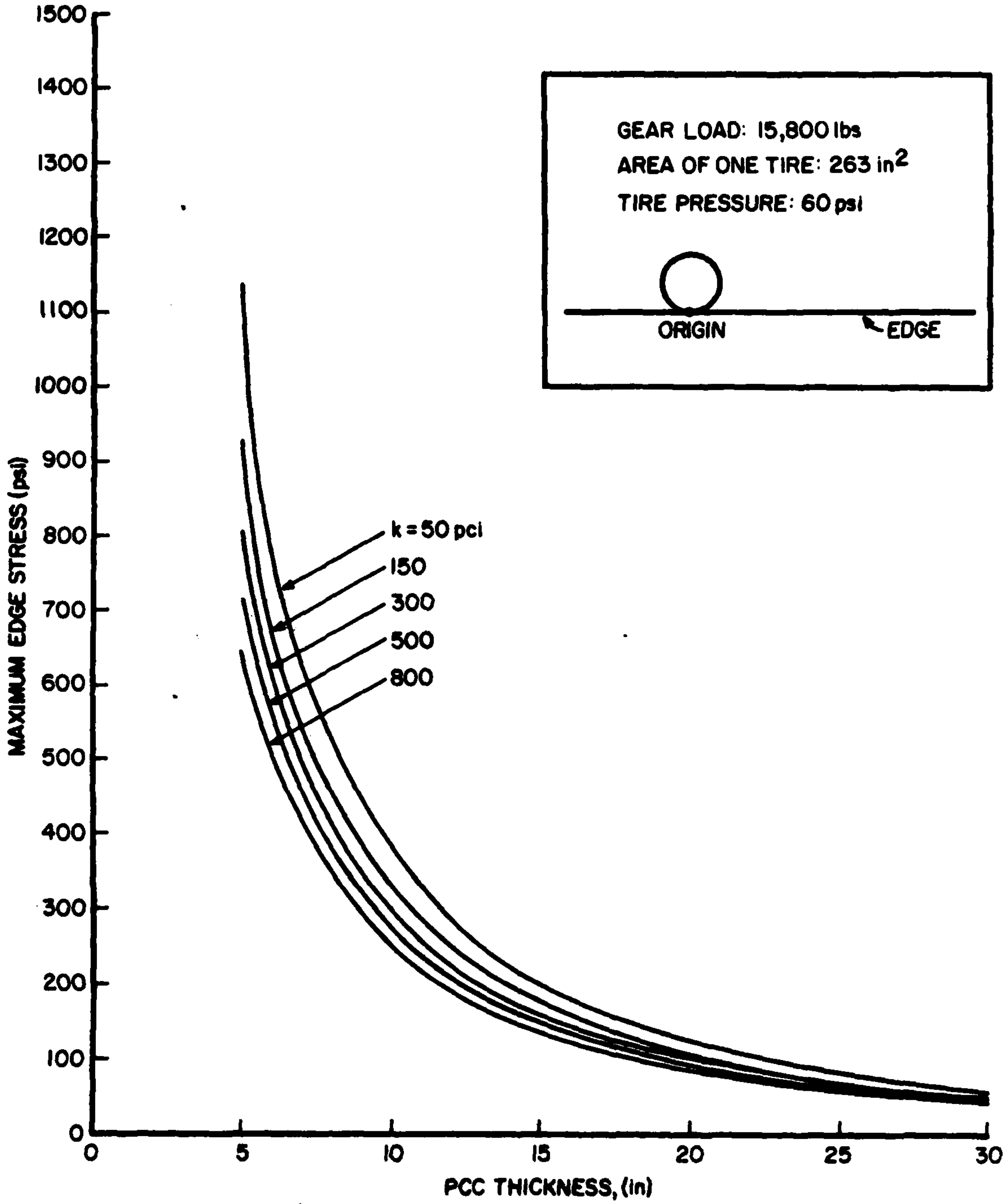


Figure B-11. Stress Chart for C-47D.

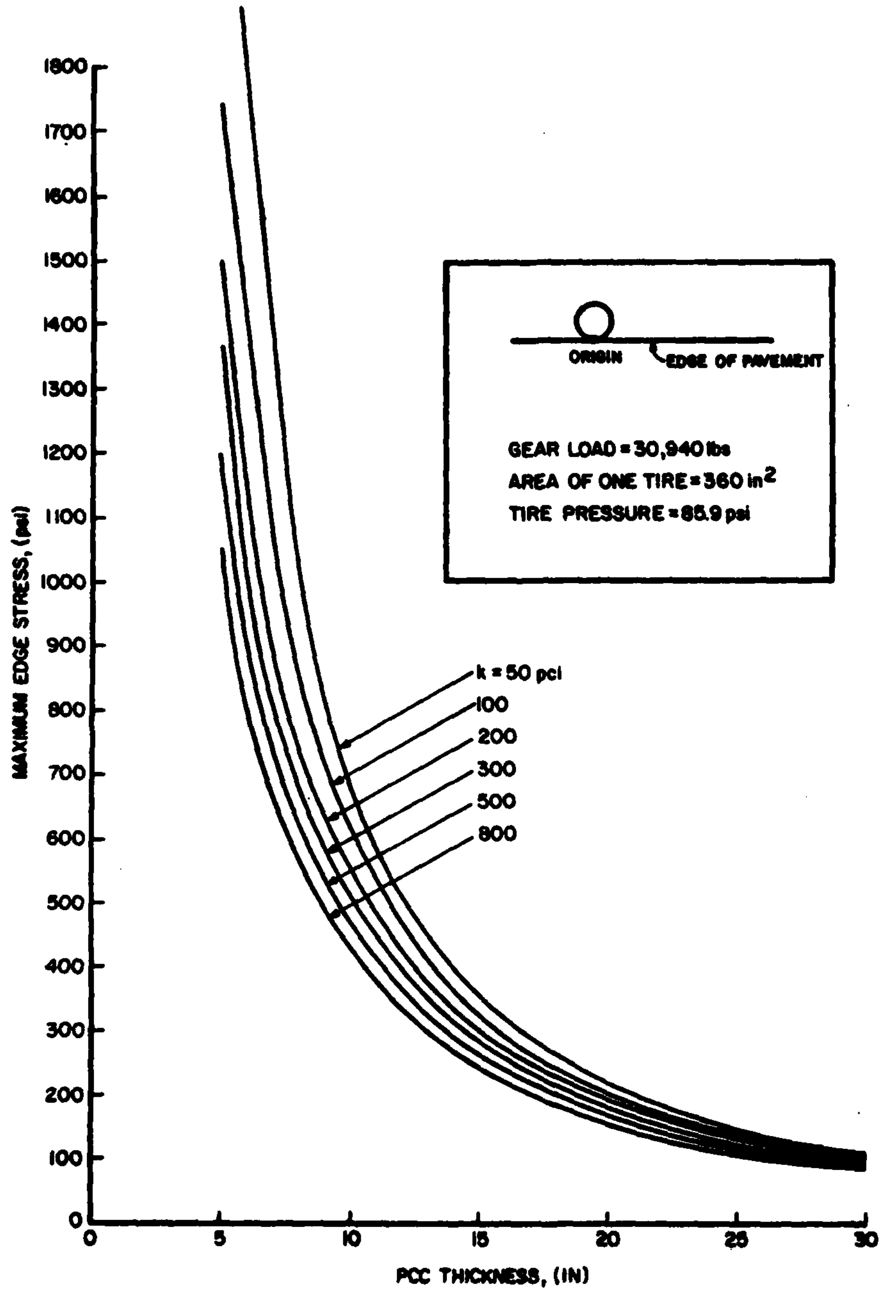


Figure B-12. Stress Chart for B-17 and B-24.

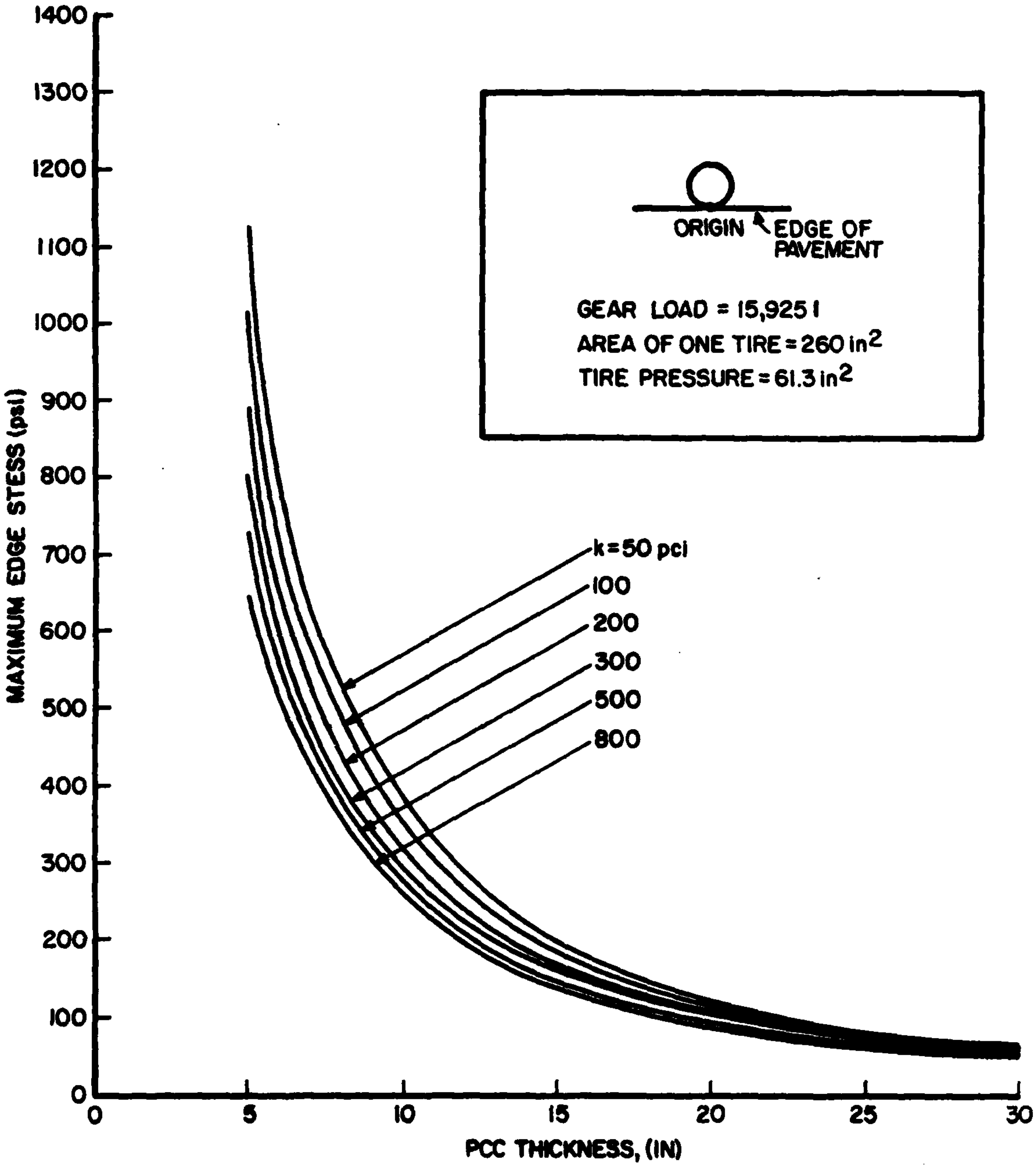


Figure B-13. Stress Chart for B-25.

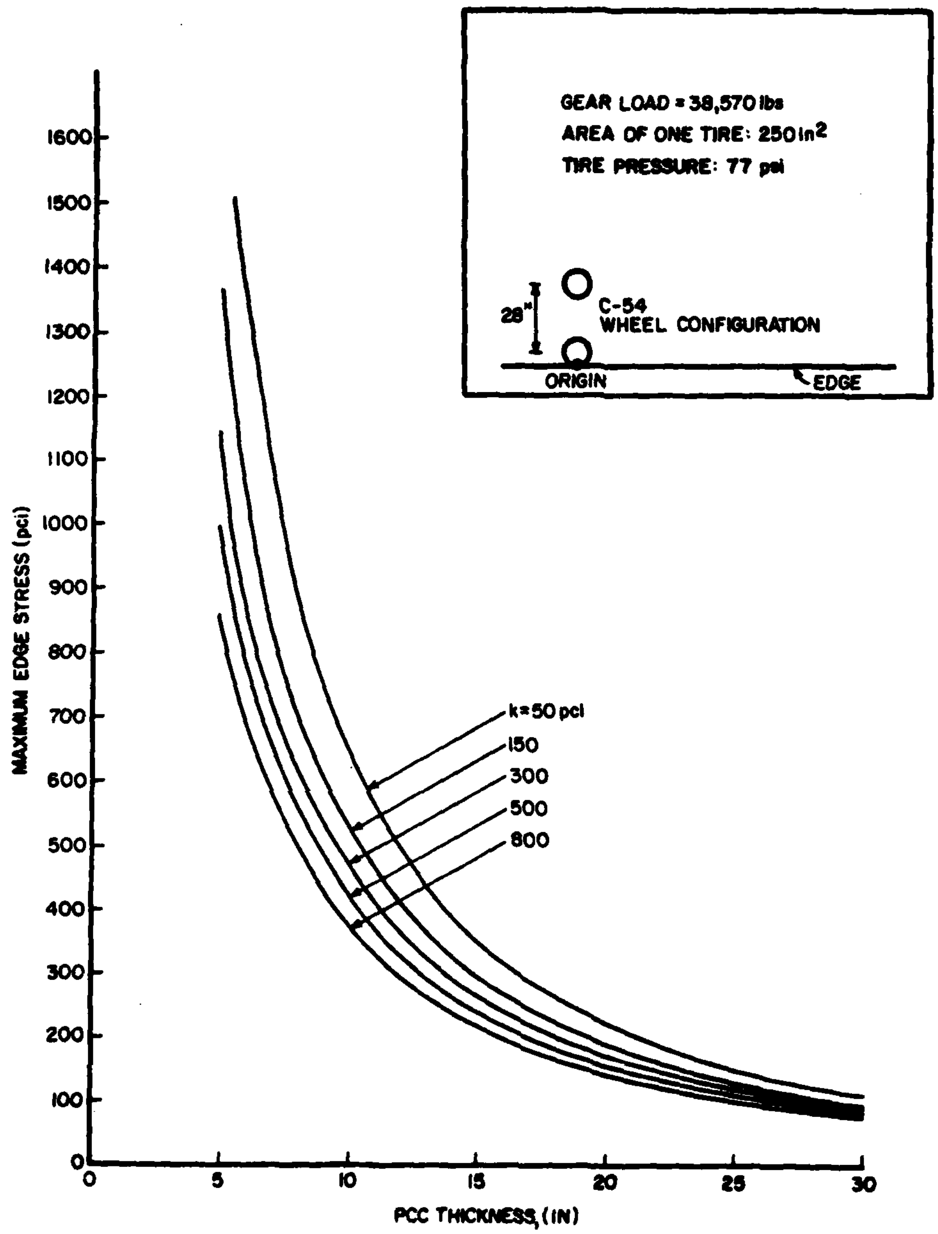


Figure B-14. Stress Chart for C-54.

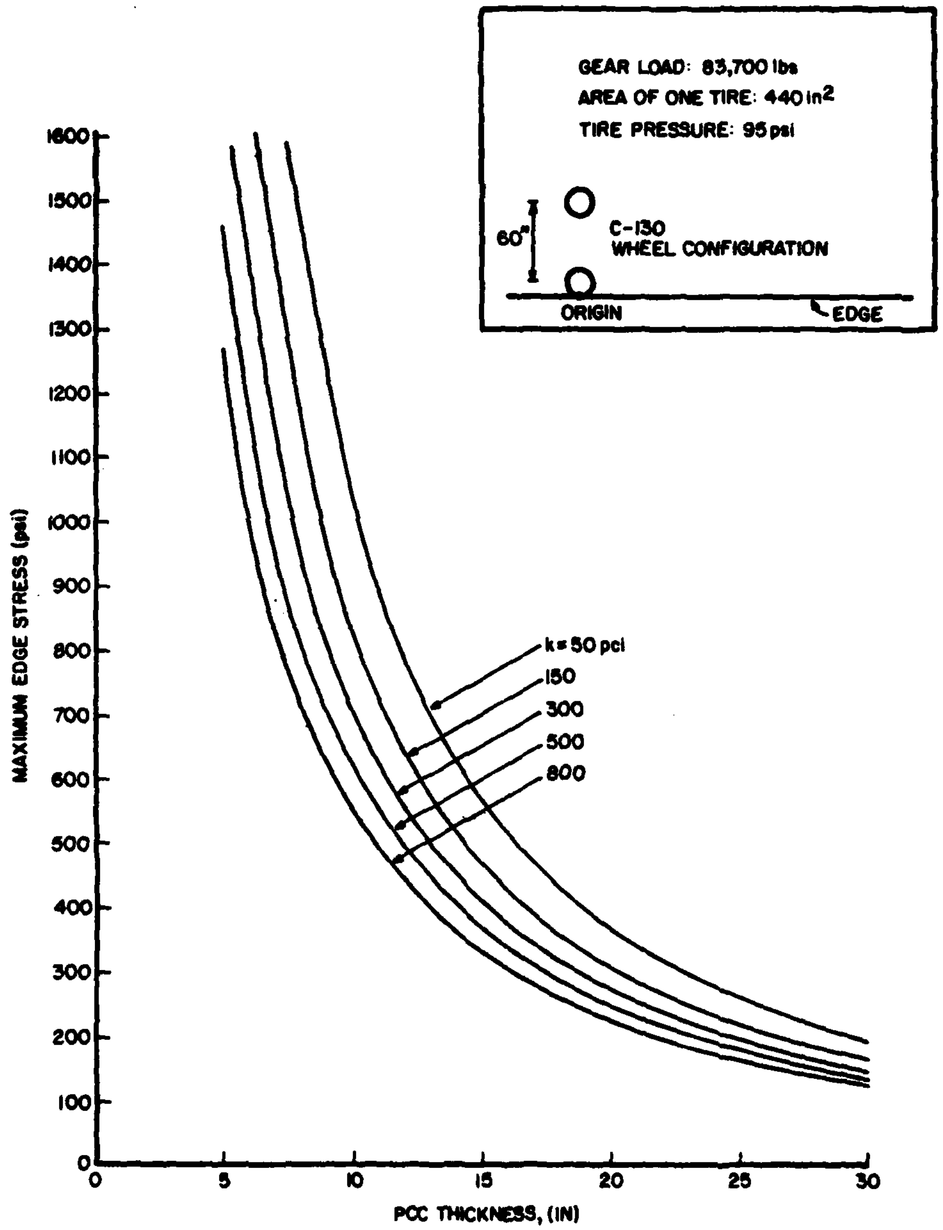


Figure B-15. Stress Chart for C-130.

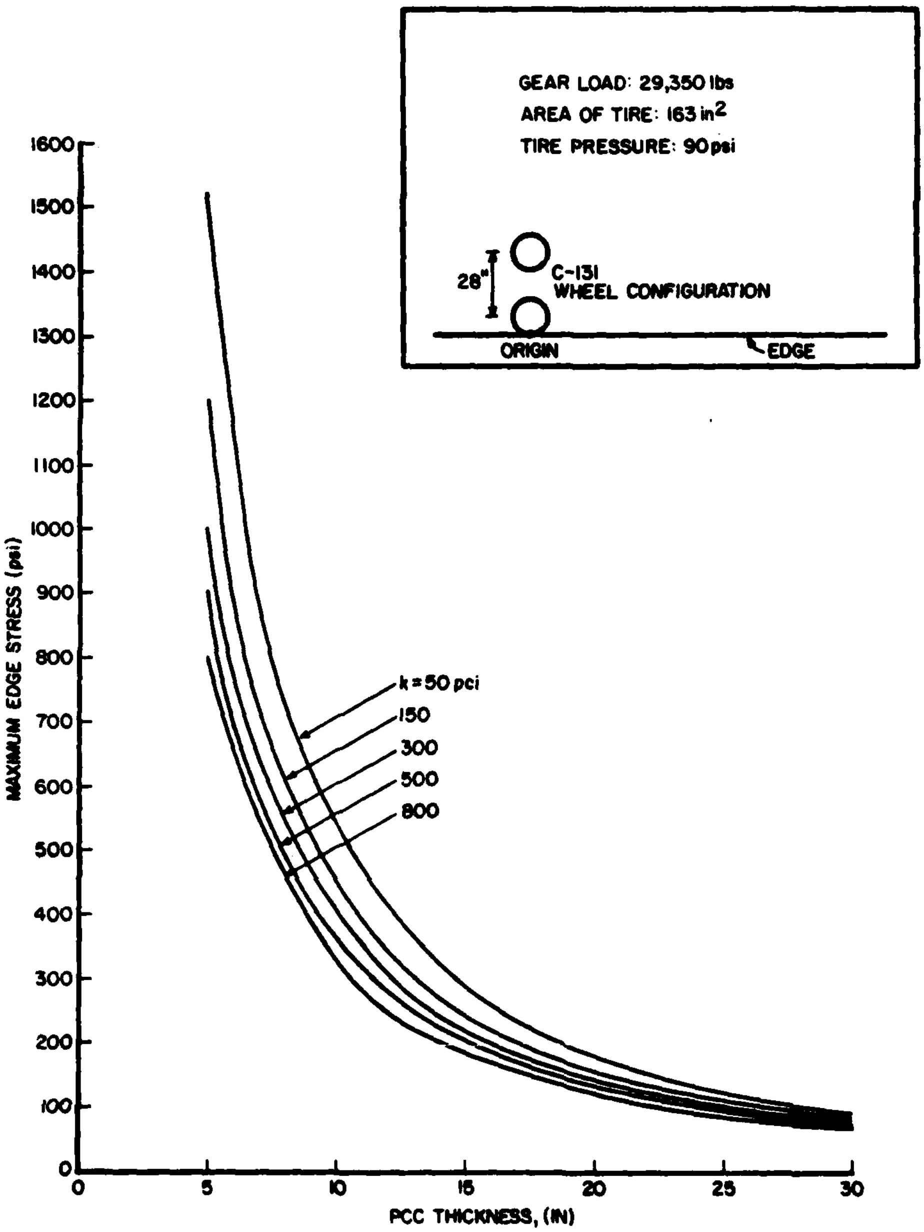


Figure B-16. Stress Chart for C-131.

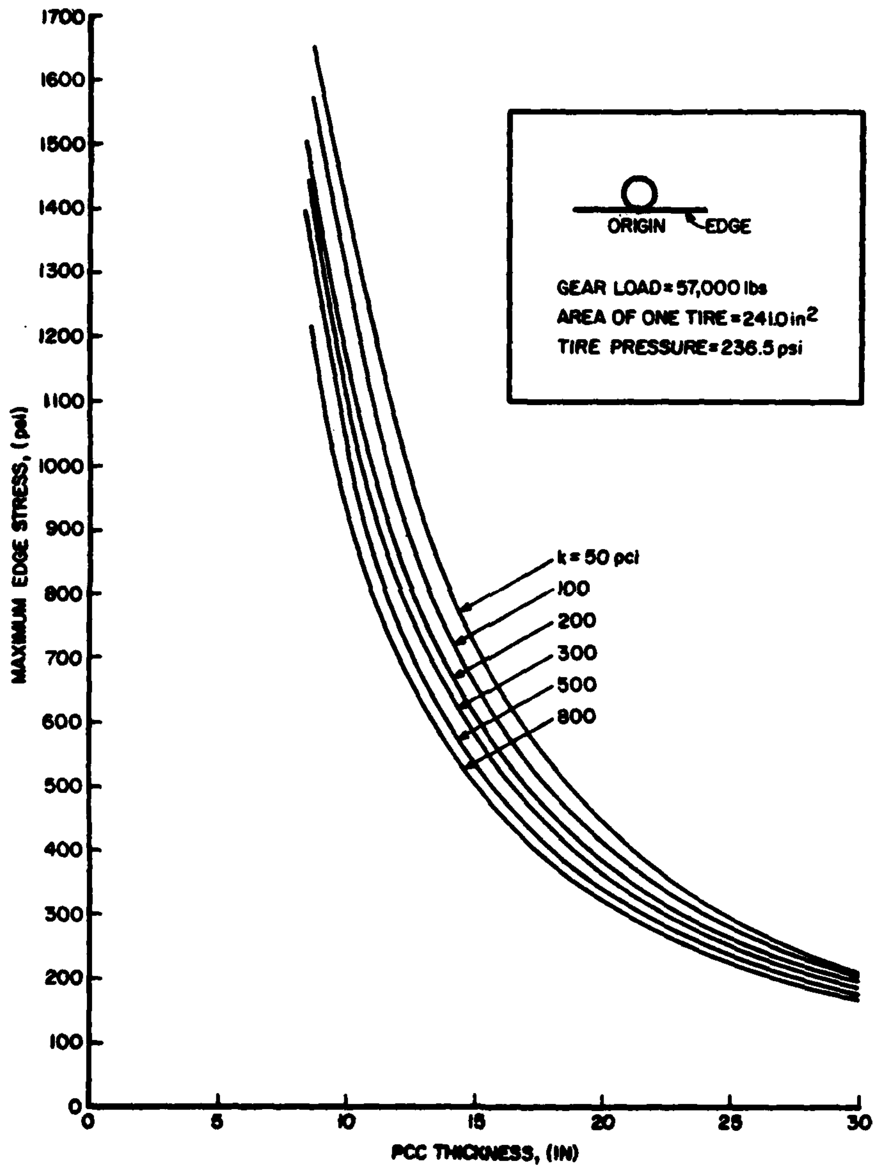


Figure B-17. Stress Chart for F-111.

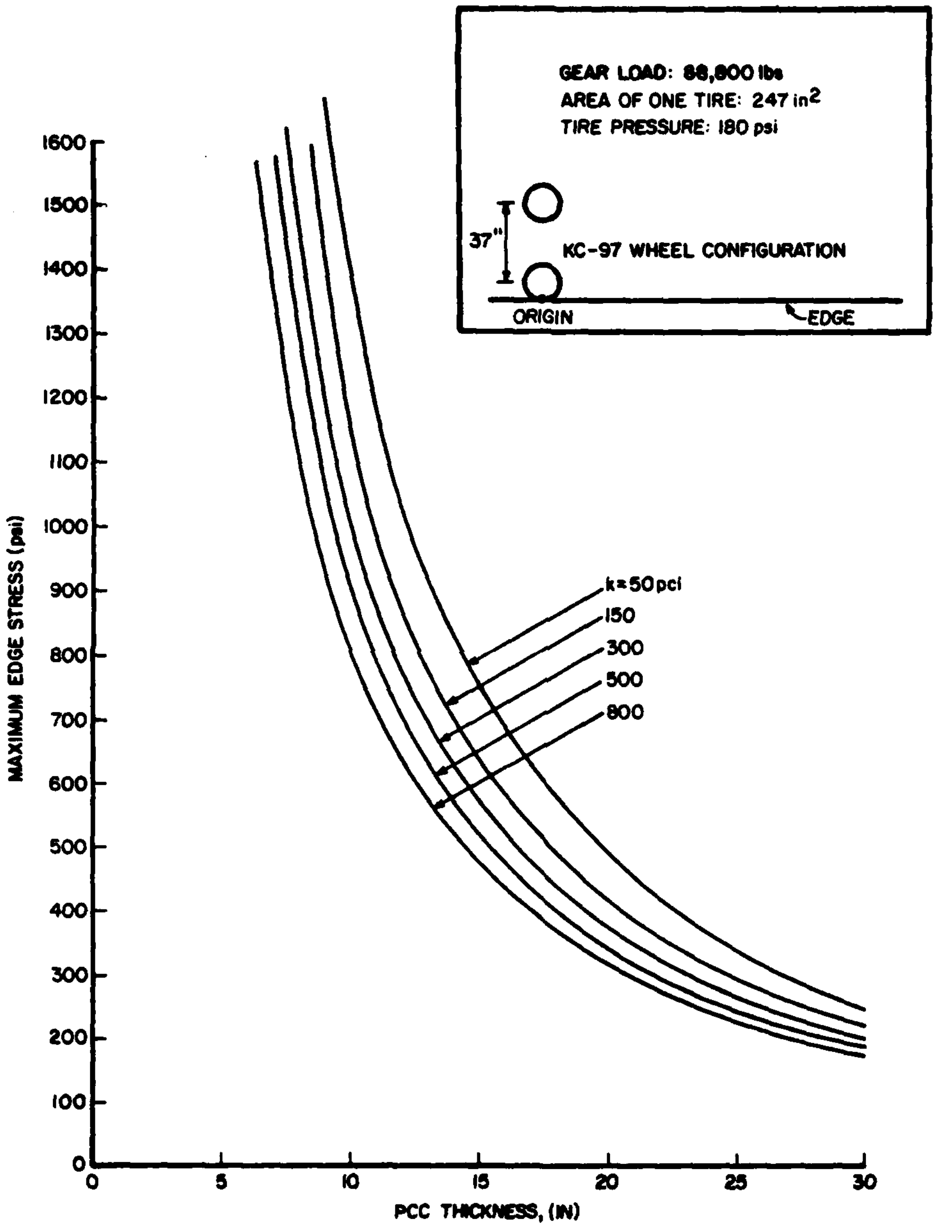


Figure B-18. Stress Chart for KC-97.

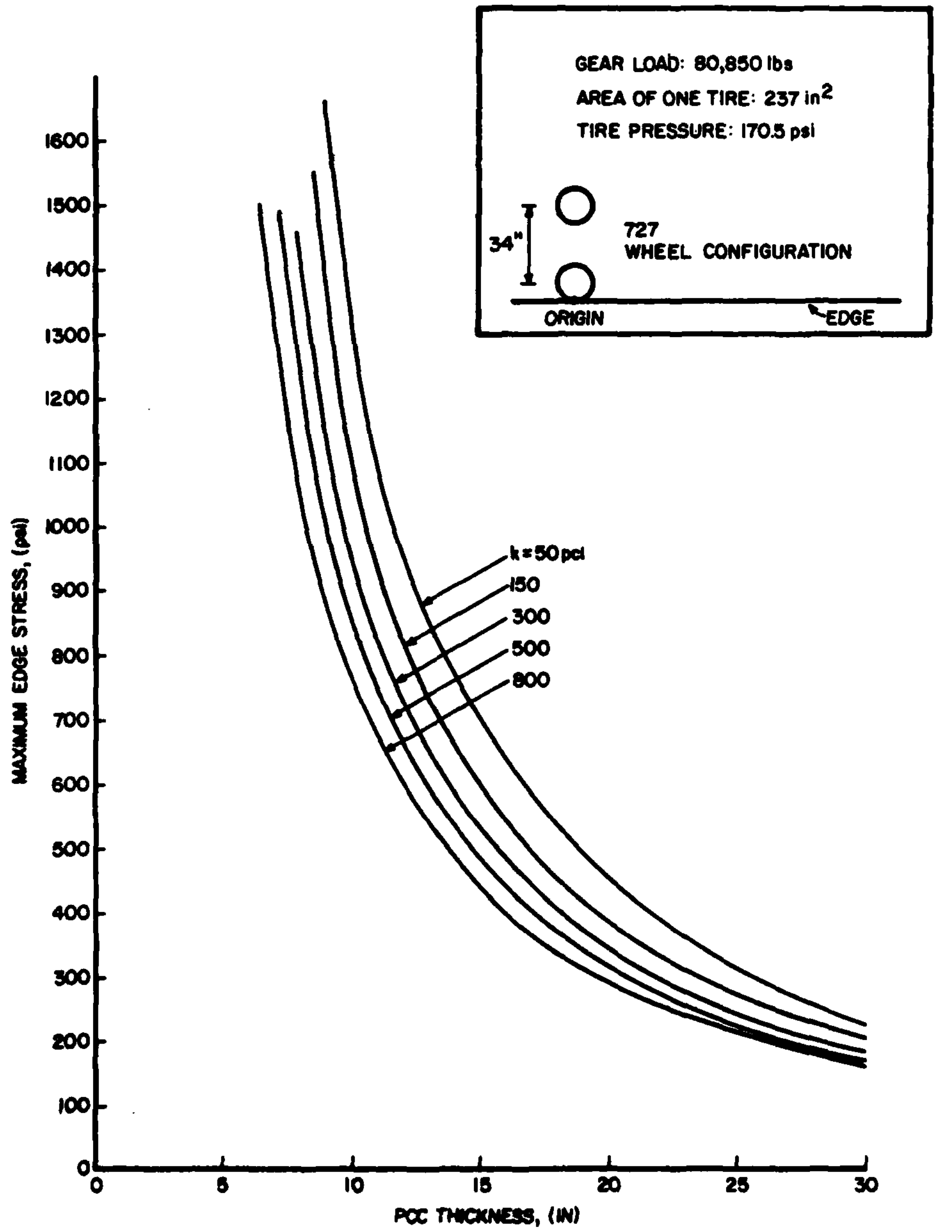


Figure B-19. Stress Chart for 727.

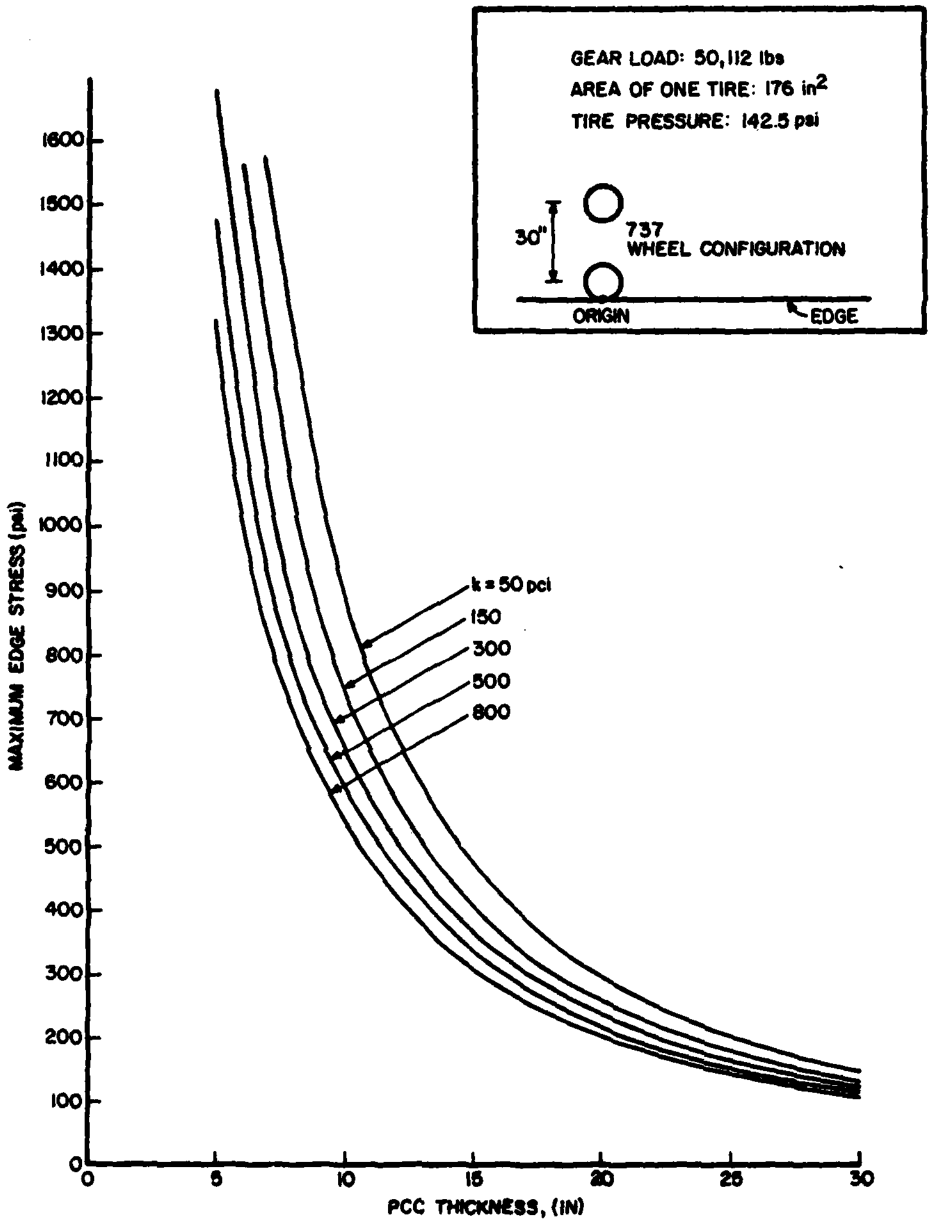


Figure B-20. Stress Chart for 737.

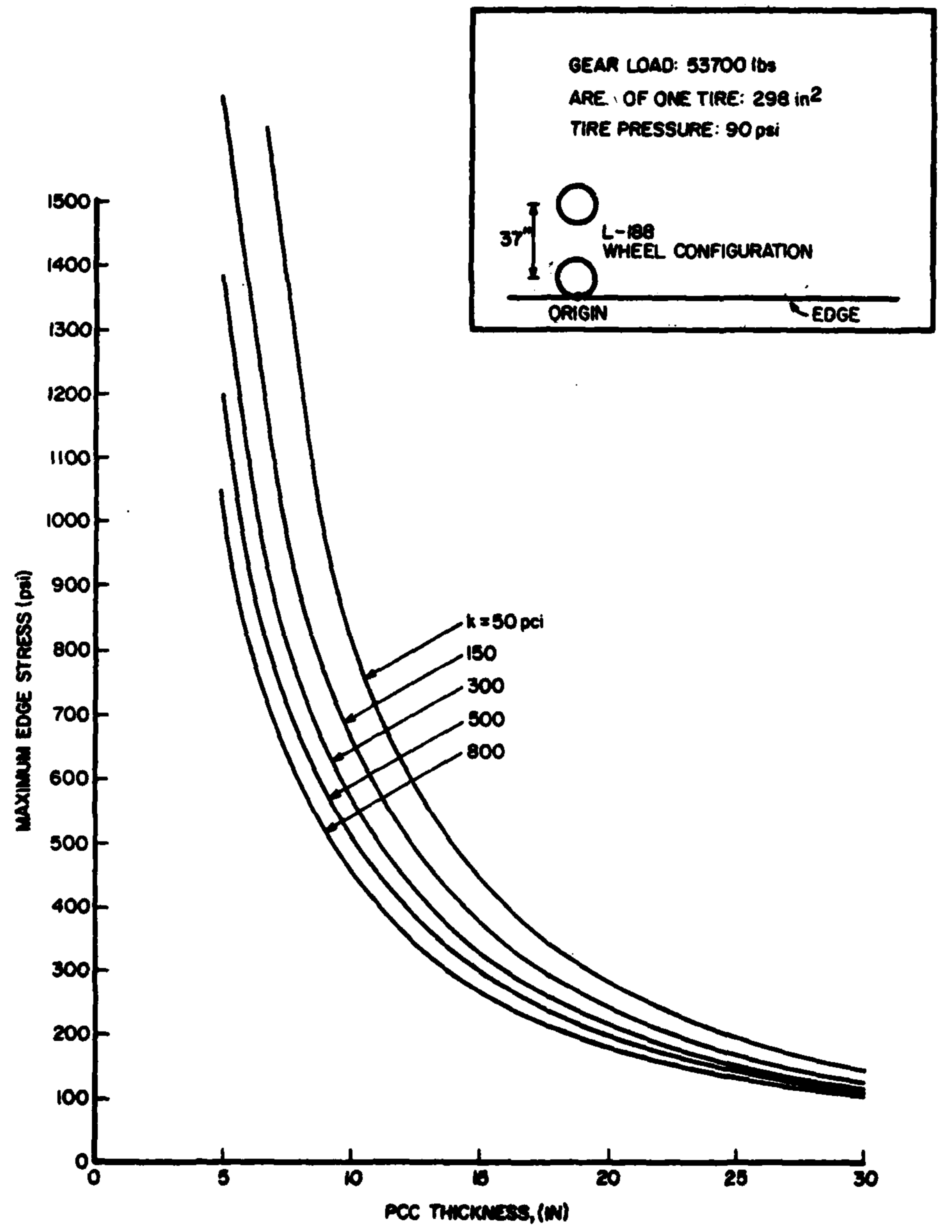


Figure B-21. Stress Chart for L-188.

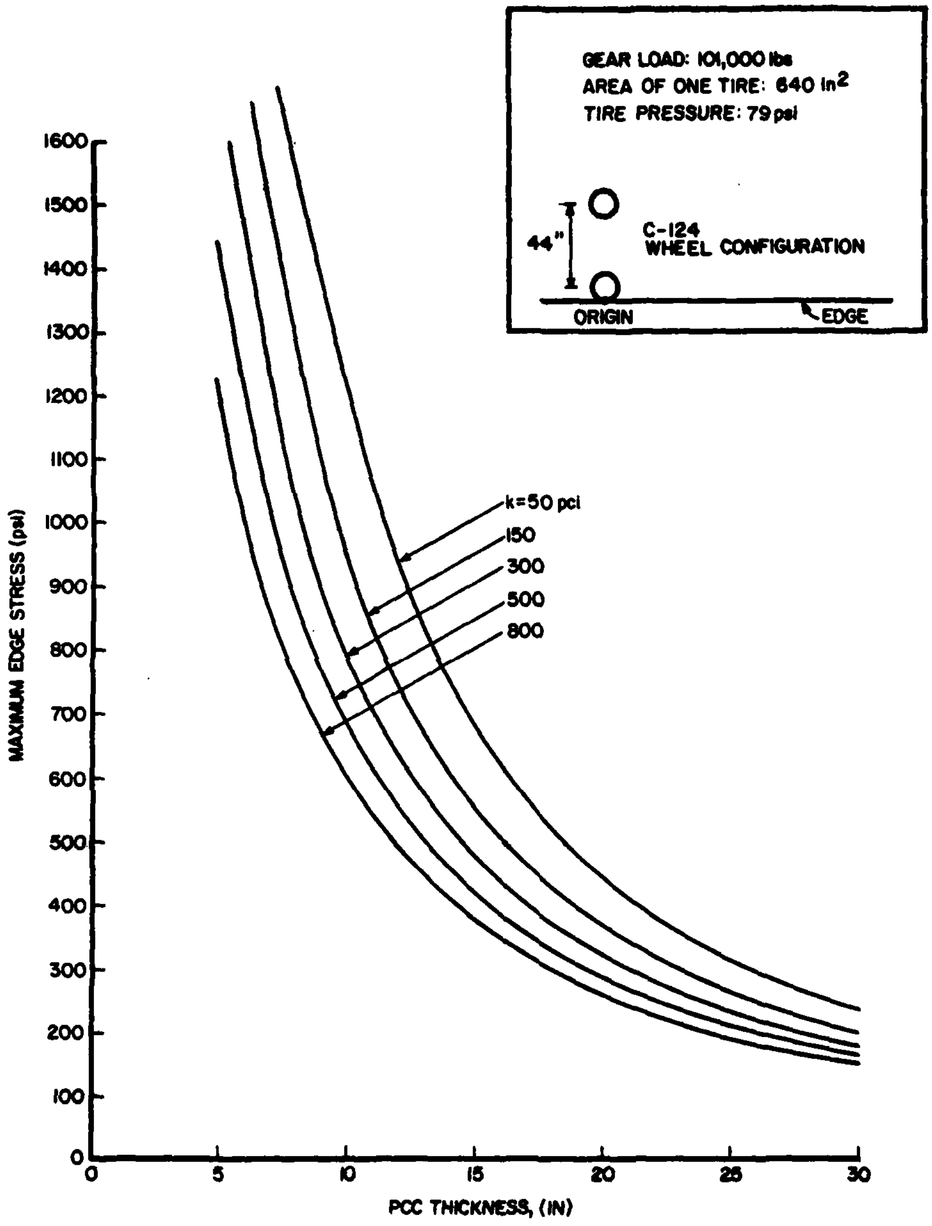


Figure B-22. Stress Chart for C-124.

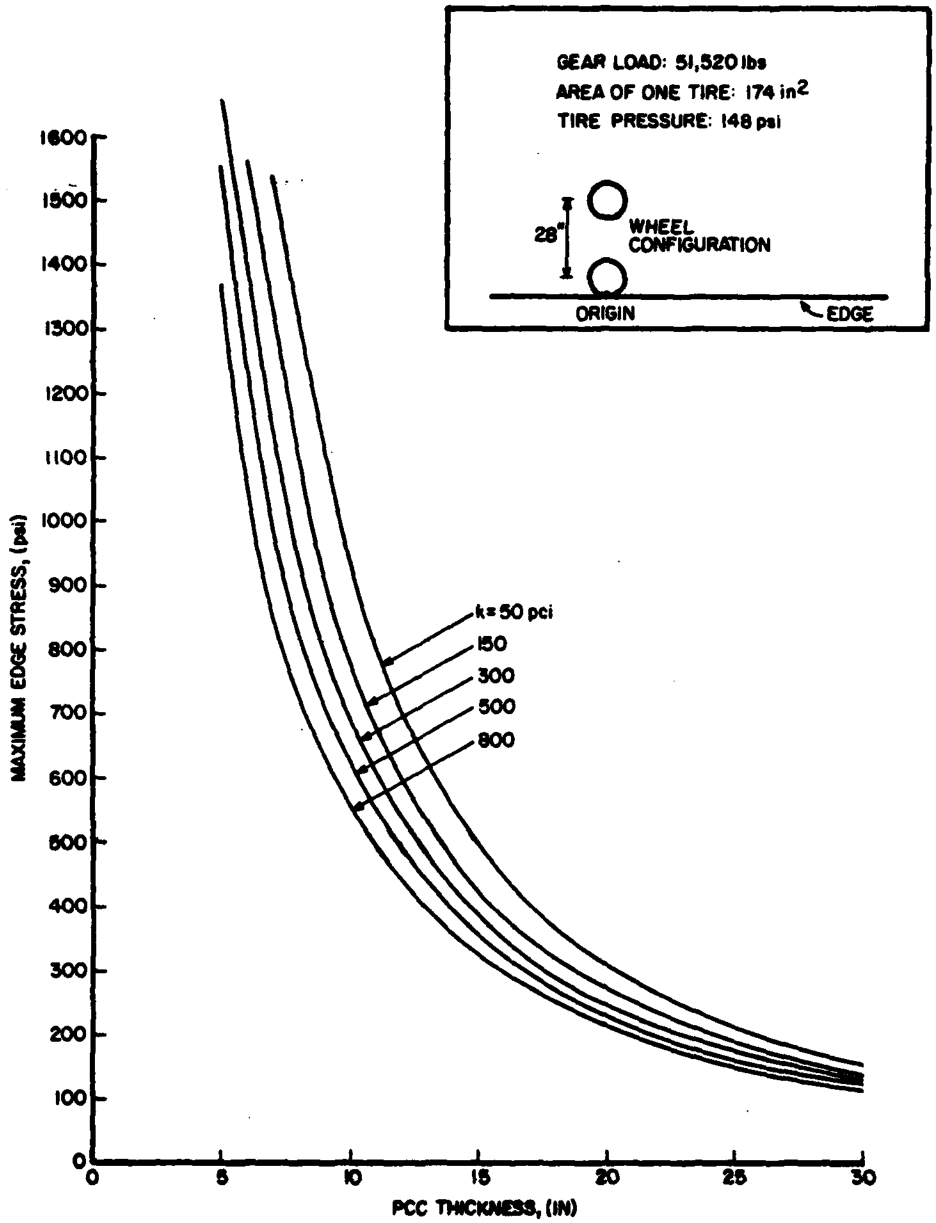


Figure B-23. Stress Chart for C-9 and DC-9.

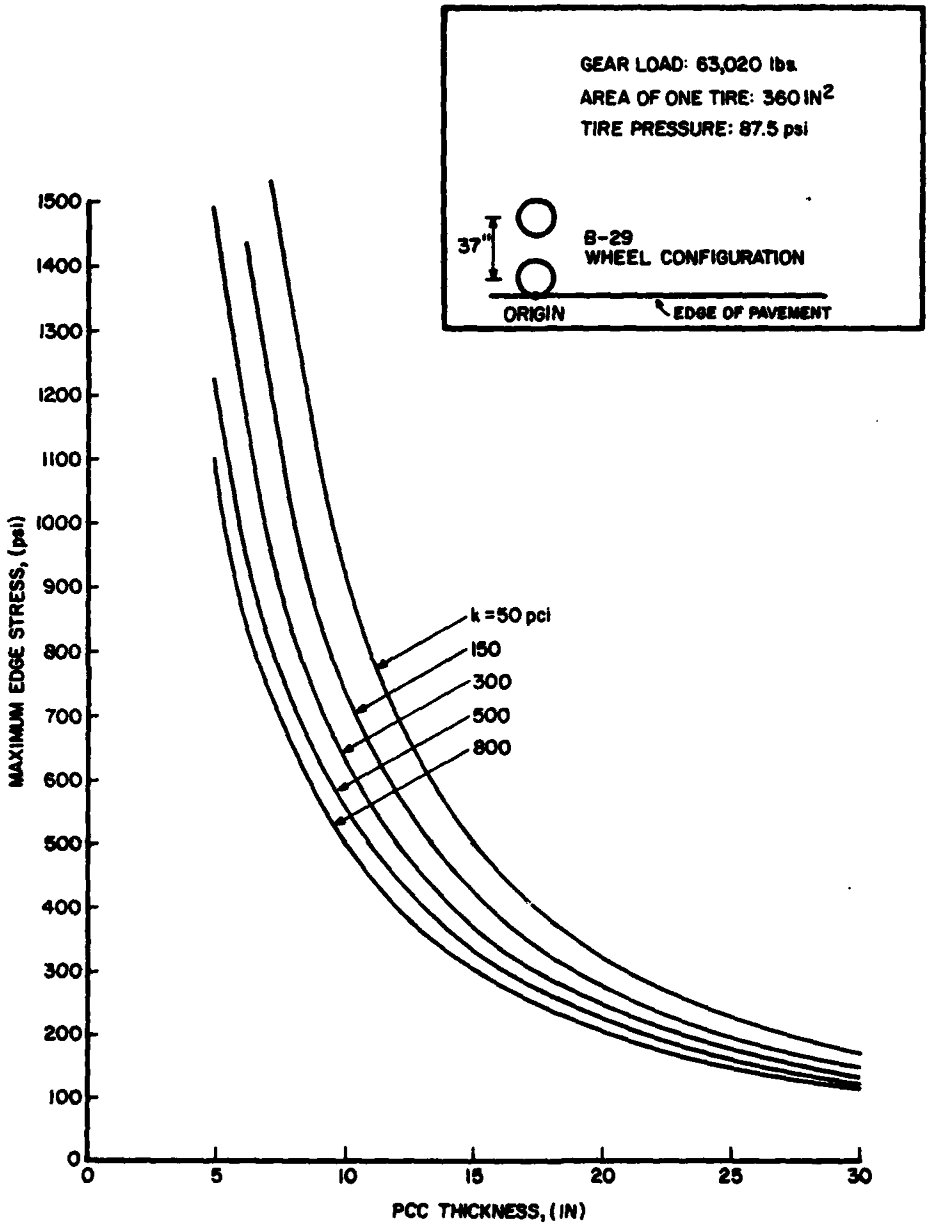


Figure B-24. Stress Chart for B-29.

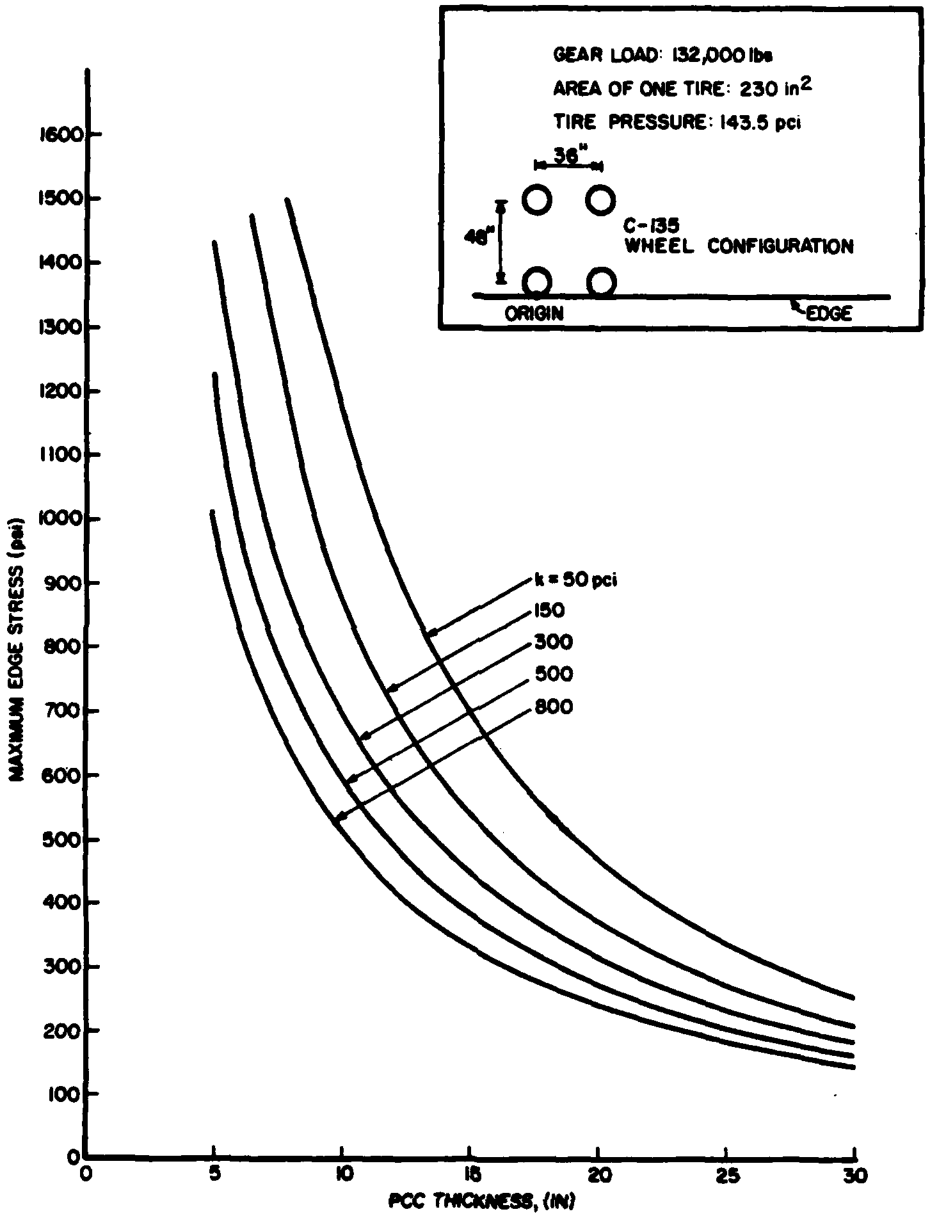


Figure B-25. Stress Chart for C-135.

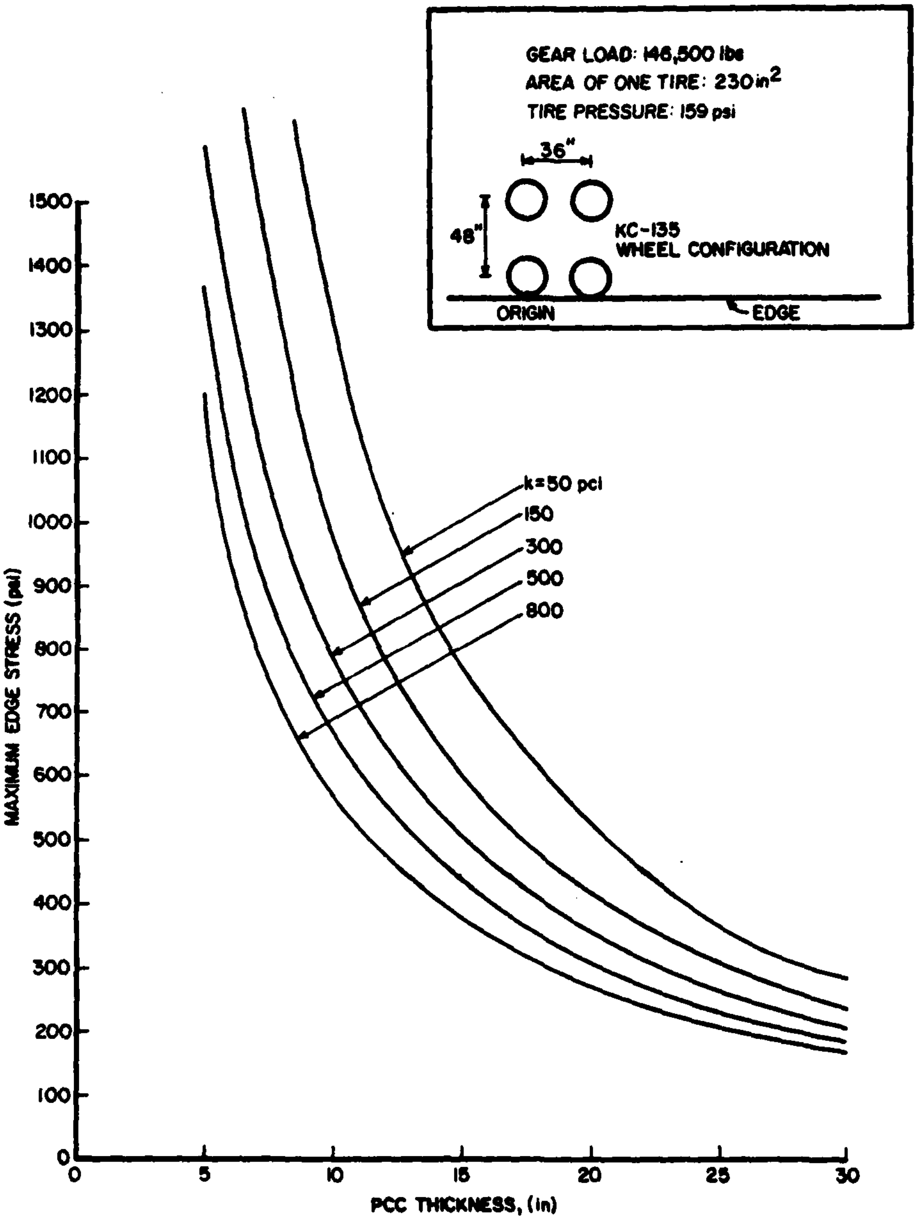


Figure B-26. Stress Chart for KC-135.

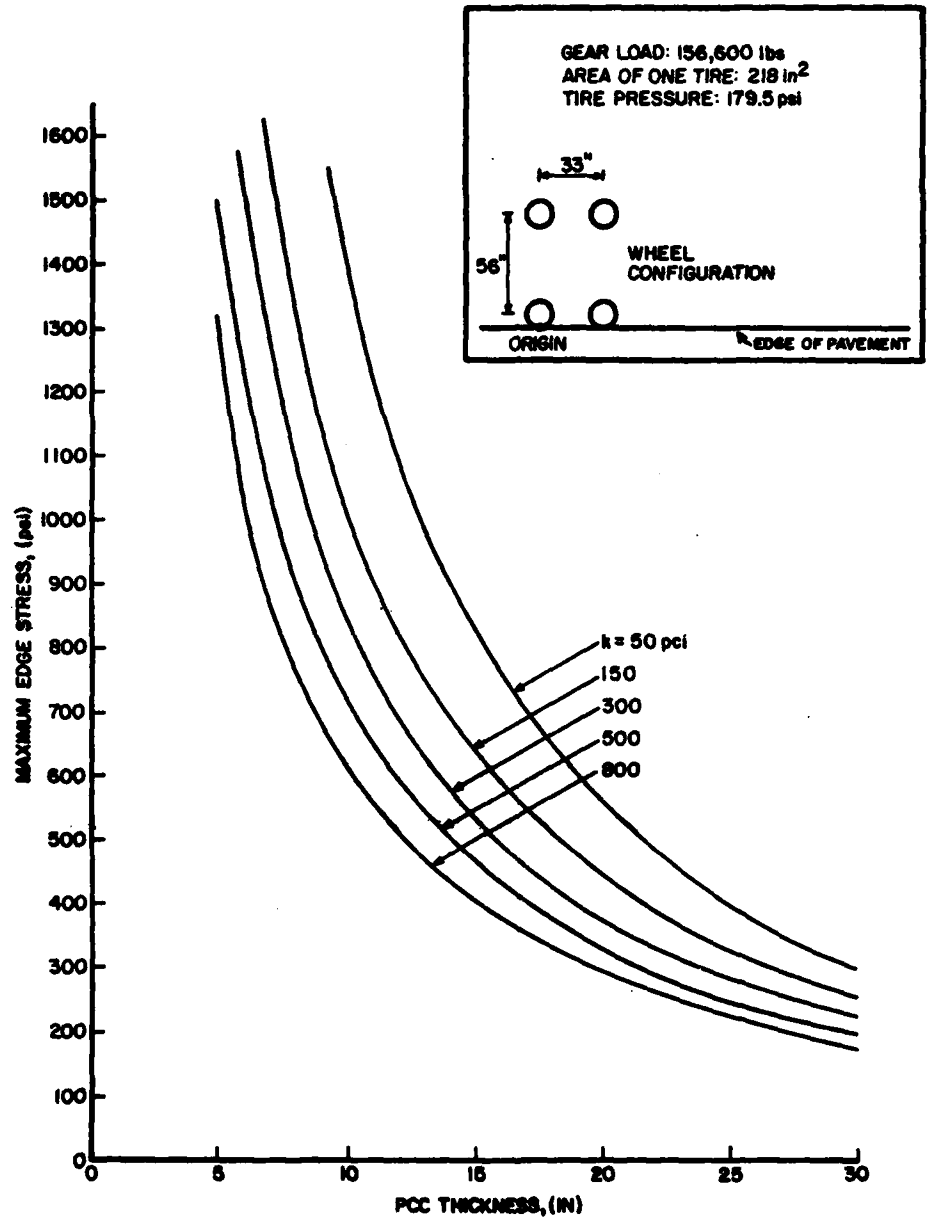


Figure B-27. Stress Chart for 707, DC-8 and B-36.

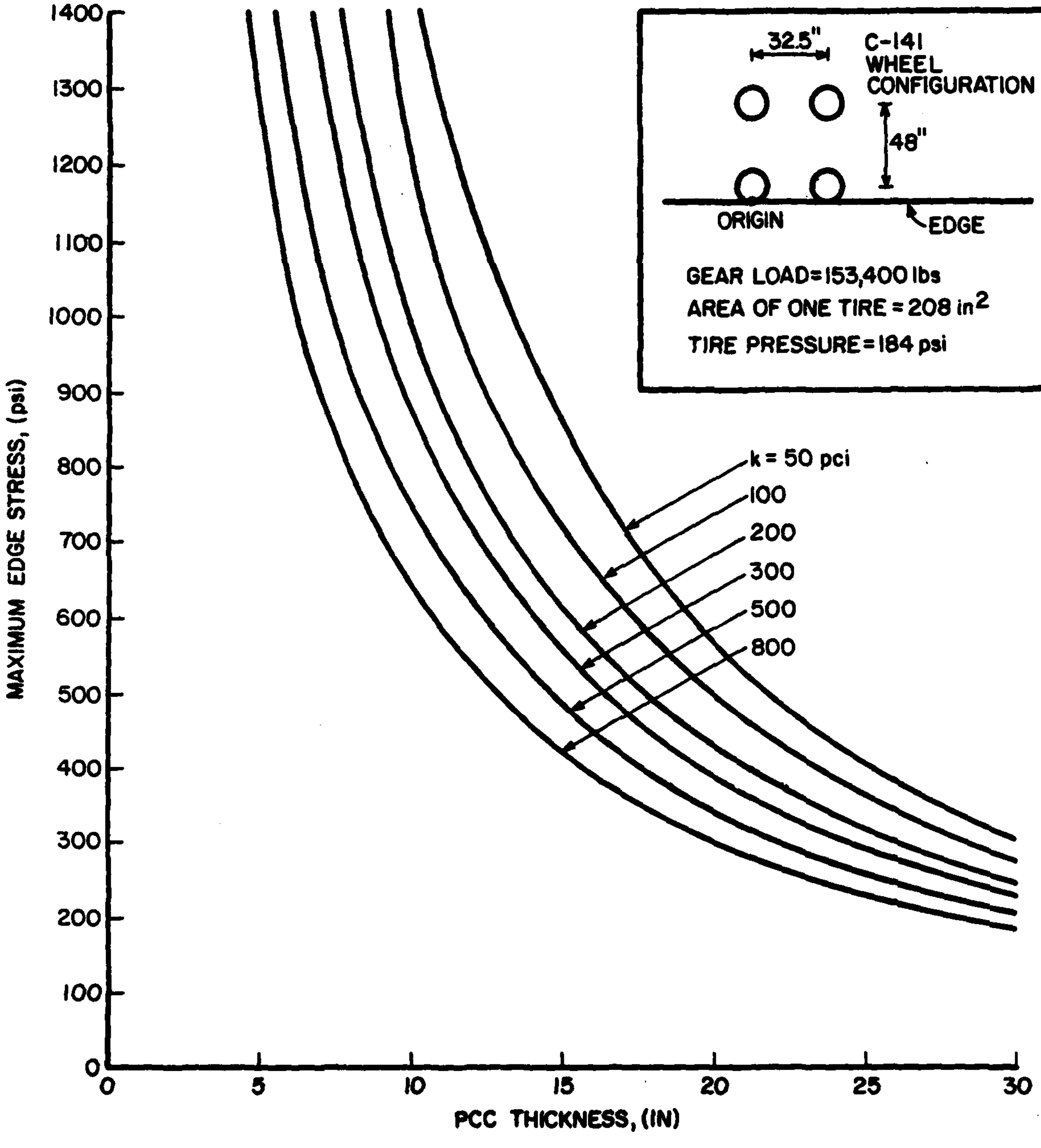


Figure B-28. Stress Chart for C-141.

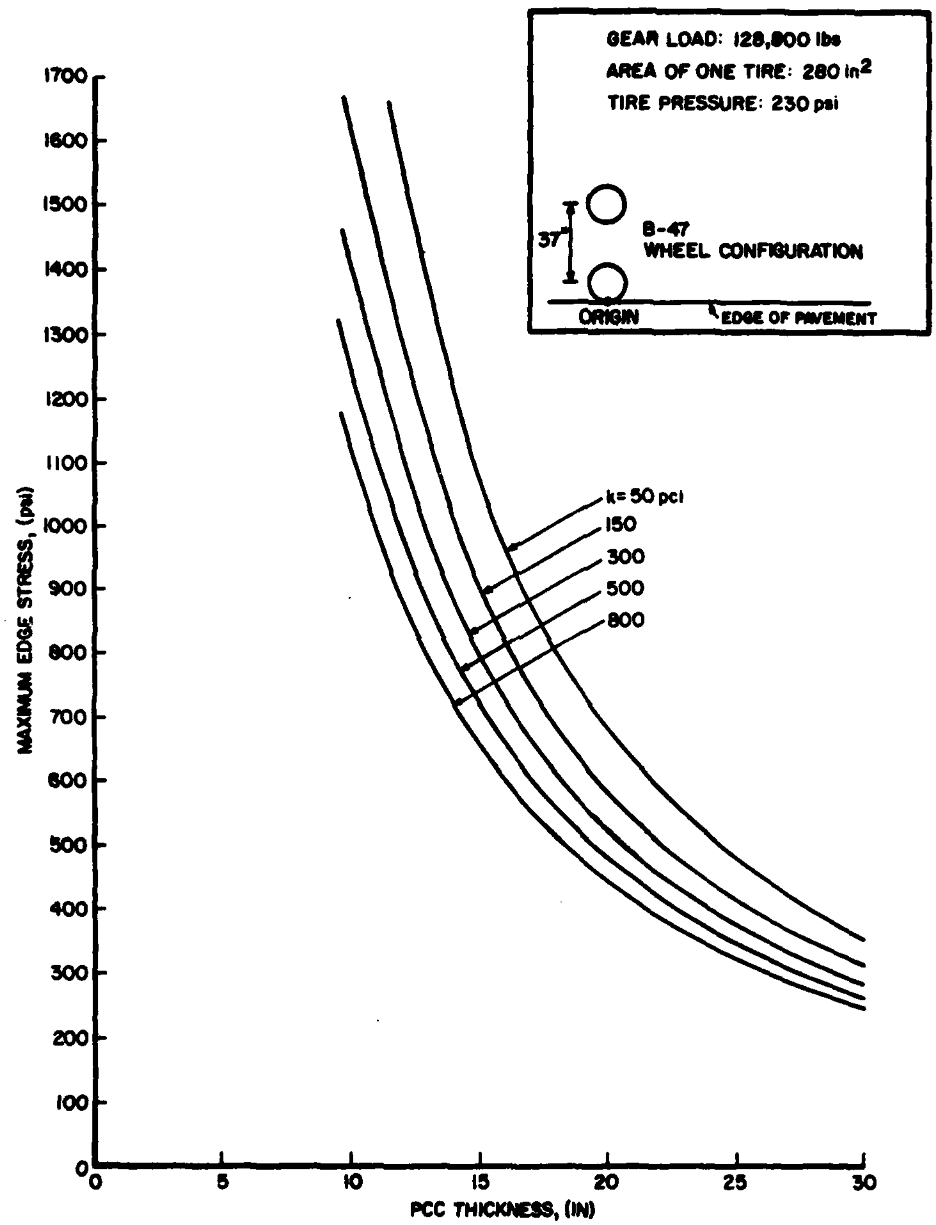


Figure B-29. Stress Chart for B-47.

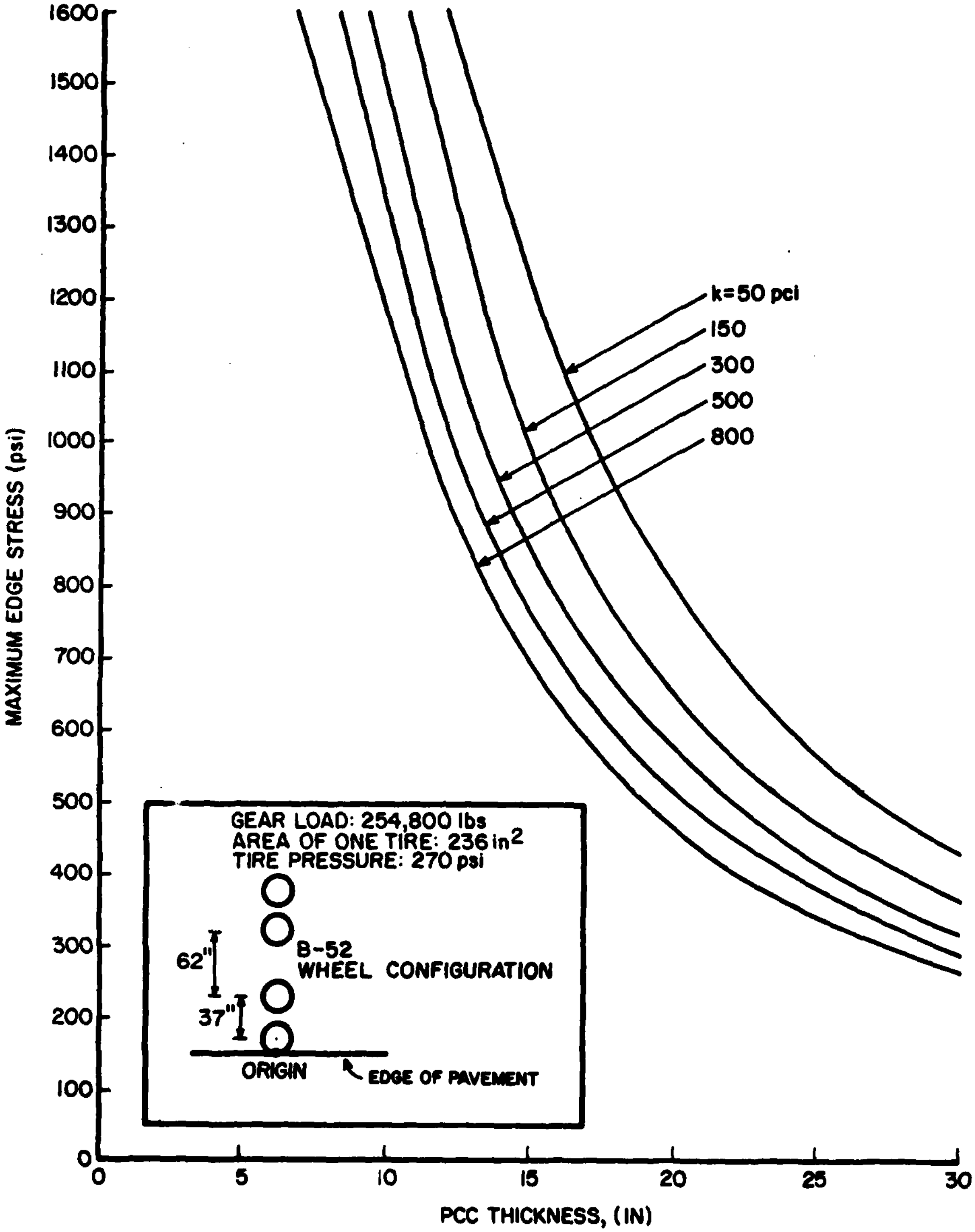


Figure B-30. Stress Chart for B-52.

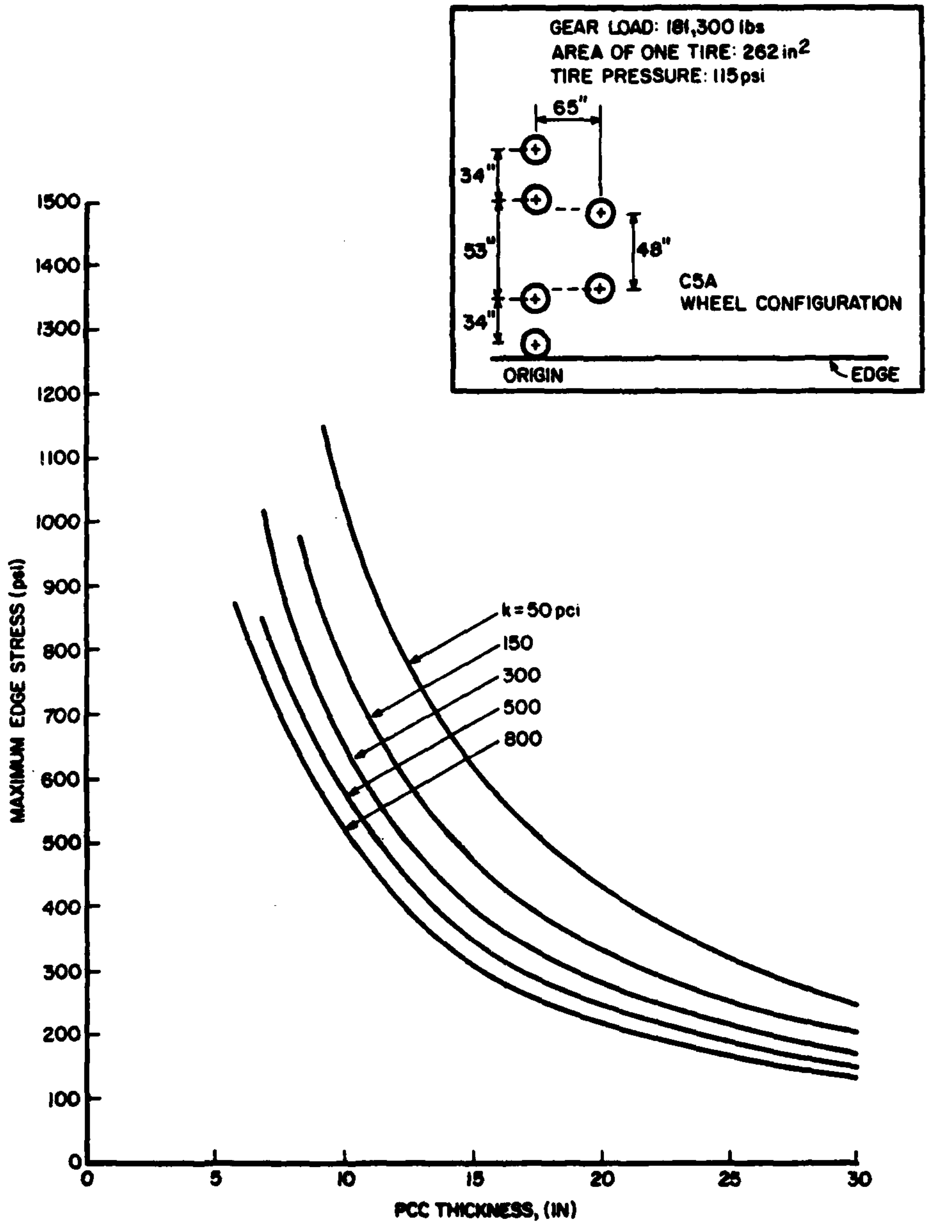


Figure B-31. Stress Chart for C-5A.

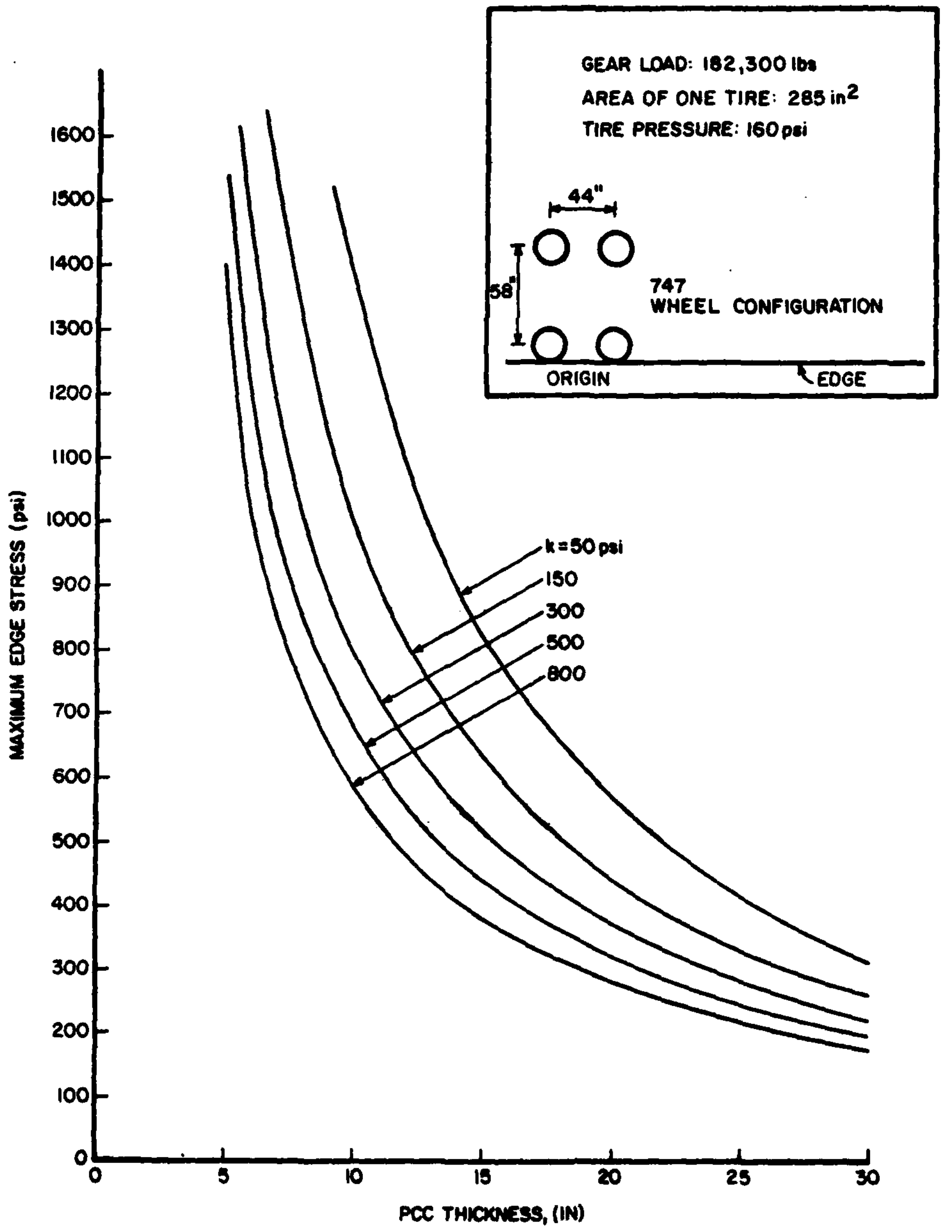


Figure B-32. Stress Chart for 747.

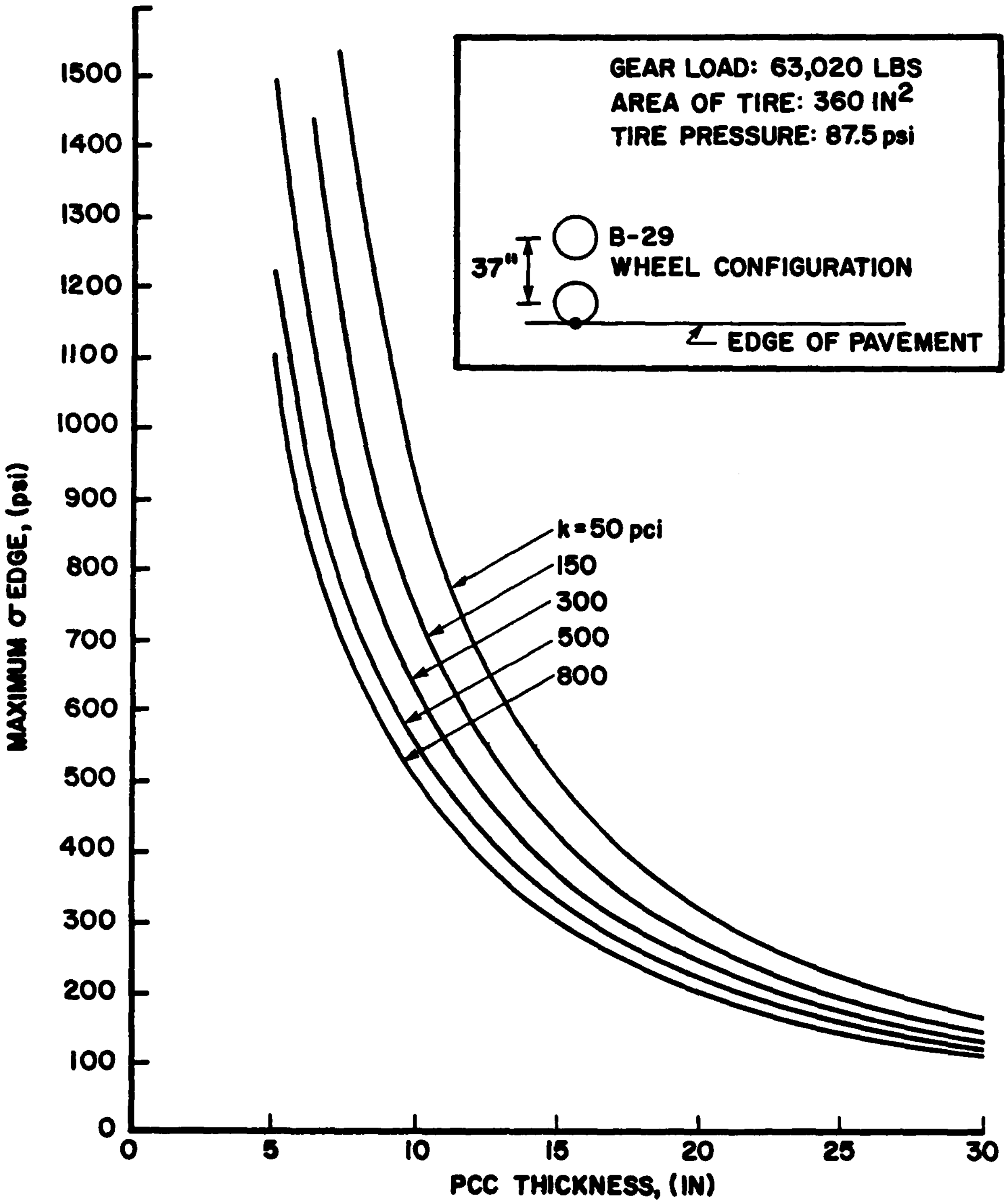


Figure B-33. Illustration To Determine Edge Stress at Bottom of Concrete Slab as a Function of Slab Thickness and Modulus of Subgrade Reaction for a B-29 Aircraft.

AD-A146 150 DEVELOPMENT OF A PAVEMENT MAINTENANCE MANAGEMENT SYSTEM 3/3
VOLUME 9 DEVELOPM..(U) CONSTRUCTION ENGINEERING
RESEARCH LAB (ARMY) CHAMPAIGN IL M Y SHAHIN ET AL.
UNCLASSIFIED MAY 84 CERL-TR-C-76-VOL-9 F/G 1/5 NL

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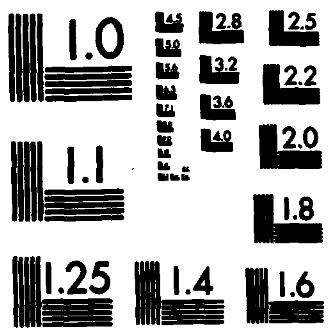


MICROCOPY RESOLUTION TEST CHART

6. Procedure Illustration

During a particular mission, a PCC pavement feature serves the following aircraft:

T-33
B-29 (See Figure B-33)
C-5A
Slab thickness: 19 inches
Modulus of subgrade reaction (K): 350 psi

Using the stress charts, the following stresses are computed:

T-33 Maximum σ_e = 65 psi

B-29 Maximum σ_e = 255 psi

C-5A Maximum σ_e = 290 psi

B. AC AND AC/AC PAVEMENTS

The analysis of AC pavements was based on linear elastic-layered theory with a modification to account for the nonlinearity of granular base and subbase materials. The four response parameters were computed for each AC pavement: (1) the maximum surface deflection, (2) the vertical stress at the top of the base layer, (3) the radial strain at the bottom of the AC layer, and (4) the vertical strain at the top of the subgrade. Response parameter compactions were carried out using the BISAR (Reference 10) computer program.

1. Asphalt Concrete Characterization

The deterioration of the AC modulus of elasticity depends on three variables: (1) thickness of AC layer, (2) mean annual solar radiation, and (3) mean annual air temperature. The procedure includes the following steps:

a. Determine a temperature increment (Δ) as a function of the mean annual solar radiation and the AC layer thickness, using Figure B-34.

b. Compute the pavement temperature as the sum of the temperature increment Δ and the mean annual air temperature:

$$T_{pave} = T_{air} + \Delta$$

c. Using the pavement temperature computed in step 2, determine the AC modulus using Figure B-35.

Table B-2 lists the average annual solar radiation and the average annual temperature for the various Air Force bases. For example, assume the following:

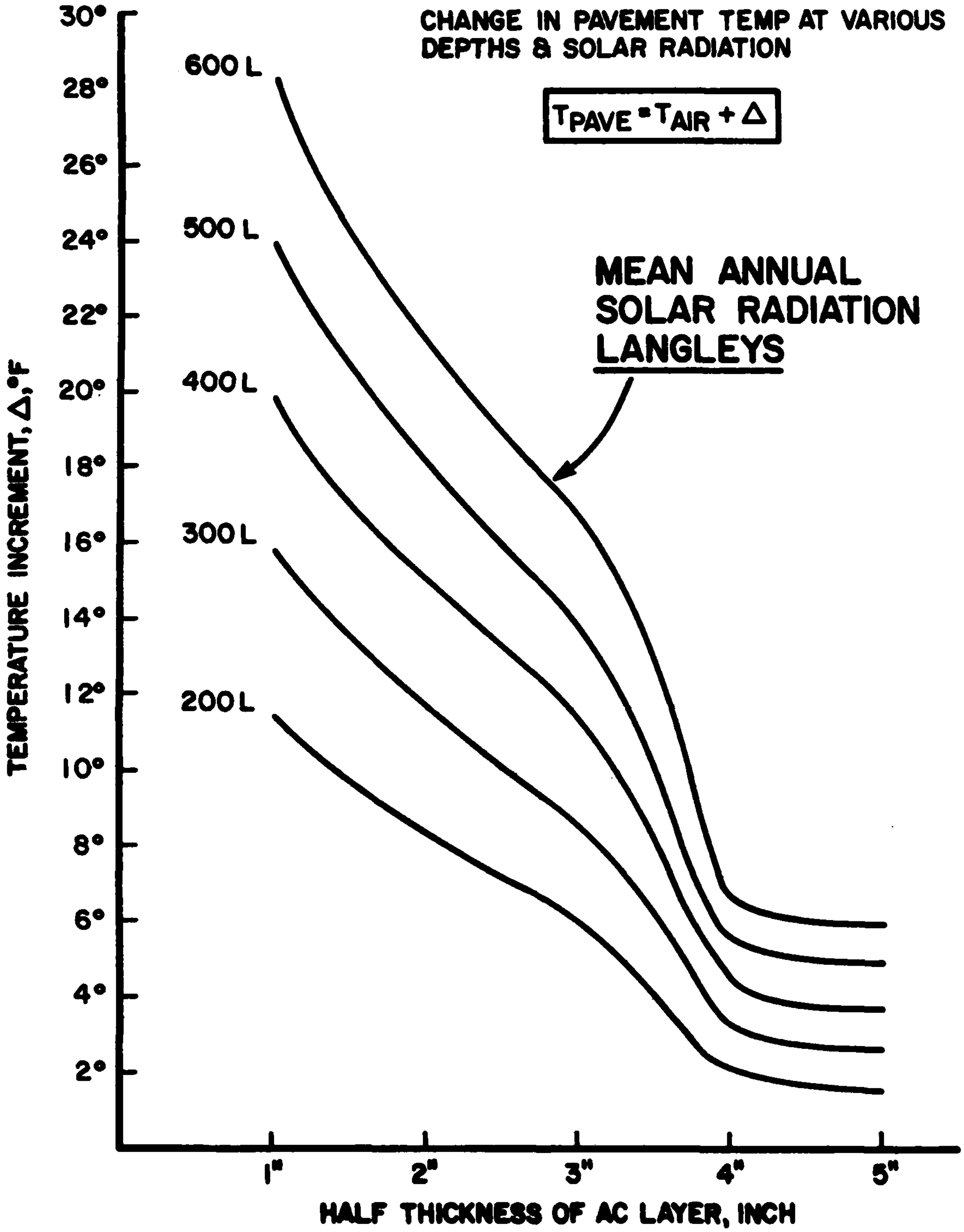


Figure B-34. Illustration To Determine Temperature Increment as a Function of the Half-Thickness of the Entire Asphalt Mat and the Mean Solar Radiation.

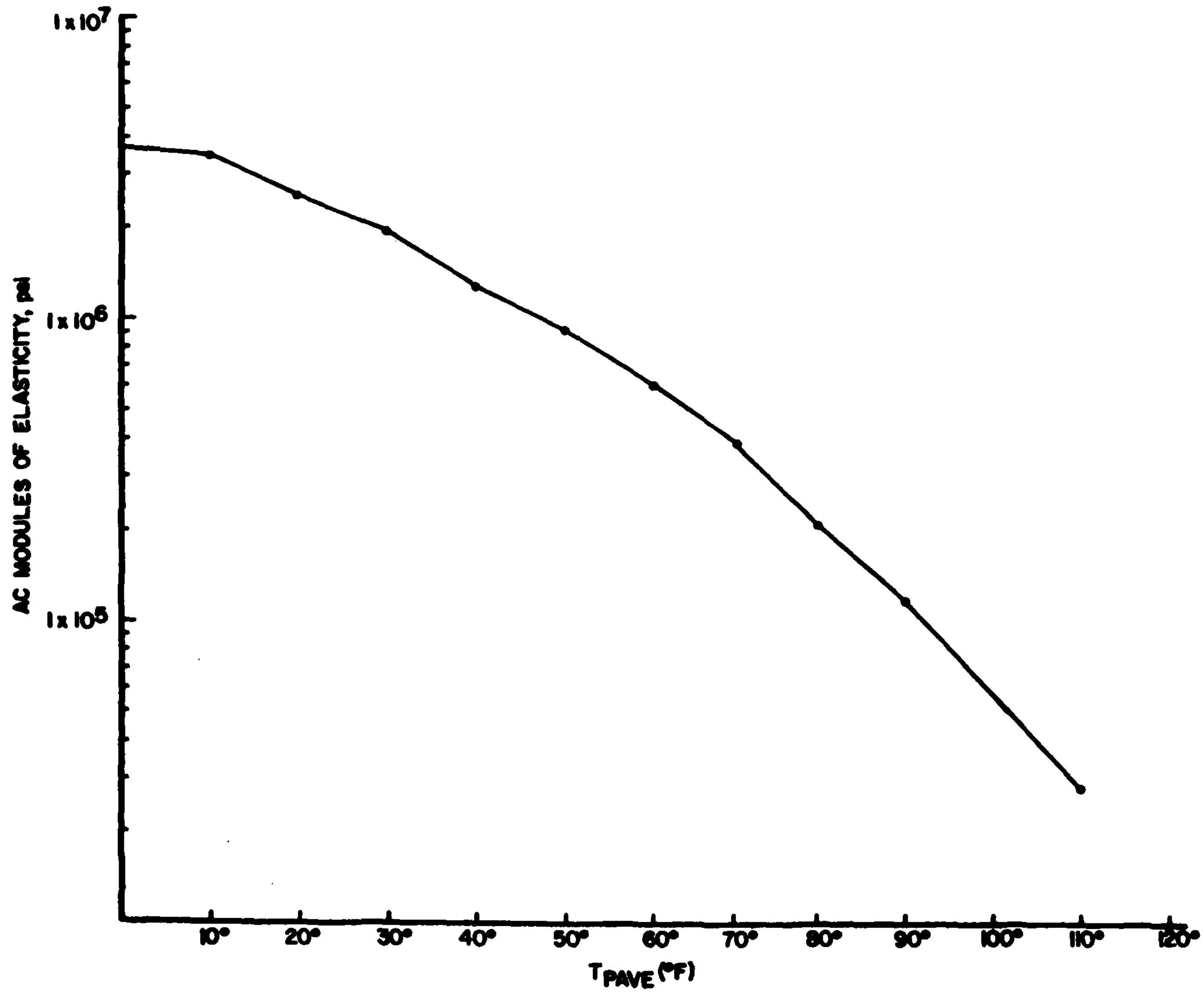


Figure B-35. Illustration To Determine the Asphalt Modulus as a Function of the Pavement Temperature Obtained From Figure B-2.

TABLE B-2. LIST OF AVERAGE ANNUAL SOLAR RADIATION AND TEMPERATURES FOR VARIOUS AIR FORCE BASES.

Base	Average Annual Solar Radiation	Average Annual Temperature
Beale	431	62.8
Charleston	404	64.7
Columbus	390	64.5
Dover	335	54.0
Hill	394	51.0
Holloman	520	61.1
Loring	316	38.4
Mt. Home	395	50.9
Nellis	509	65.8
Robins	412	65.1
Sheppard	440	64.1

Thickness of AC layer: 3 inches.

Mean annual solar radiation: 350 Langleys.

Mean annual air temperature: 55°F.

Enter Figure B-34 with 1.5 inches (3 inches/2), intersect 350 Langleys, and find Δ = 14.3°F.

Thus, Δ Pave = 55 + 14.3 = 69.3°F.

Enter Figure B-35 with 69.3°F and find E_{AC} = 390,000 psi.

A Poisson's ratio of 0.35 was assumed for the AC layer.

2. Granular Materials Characterization

A special study was performed to estimate the E-value of granular materials for input to the elastic layer program. Analyses based on ILLI-PAVE (a stress-dependent finite-element module at the University of Illinois) were conducted for typical pavement sections. The resulting E-value of the granular material was found to be primarily a function of the aircraft loading, the thickness of the AC layer, and the modulus of the AC layer.

Table B-3 shows the generalized types of aircraft loading which were established. The aircraft loading type is determined,based on the Equivalent Single-Wheel Load (ESWL) and the contact pressure. Aircraft type can be determined using the following guidelines:

Aircraft Loading Type	ESWL (kips)	Tire pressure (psi)
A	ESWL $\leq$ 75	p $\leq$ 140
B	ESWL $\leq$ 75	140 < p $\leq$ 225
C	ESWL > 60	p > 225
D	ESWL $\leq$ 60	p > 225

TABLE B-3. AIRCRAFT LOADING CHARACTERIZATION FOR AC PAVEMENT ANALYSES.

Aircraft	Aircraft Type	ESWL (lbs)	Tire Pressure (psi)
T-33/F-80	A	7,050	132
T-37	A	3,800	85
T-38	D	5,700	248
T-39	B	9,450	180
F-4/F-15	D	25,500	225
F-Series	D	27,000	270
F-111	B	46,500	150
F-86/F-102/F-106	B	11,350	180
F-105	B	23,400	215
C-47	A	15,800	60
C-123	A	25,300	90
B-24/B-17	A	31,000	86
B-25	A	16,000	61
T-39	A	15,700	122
C-9A/DC-9	B	35,500	204
C-130	A	48,500	110
C-131	A	18,600	114
KC-97/C-135/C-133	B	54,200	220
C-54G	A	23,700	95
L-188	A	33,000	111
B-47	C	79,800	285
C-124	A	62,600	98
737	B	32,000	182
727	B	50,000	210
B-29	A	39,700	110
707/B36/DC-8	D	58,000	266
KC-135	D	54,200	236
C-141	D	59,000	284
B-52	C	89,200	378
C-5A	C	65,200	249
747	C	80,200	281

The equivalent E-modulus of a granular layer is determined, using Figure B-36. Thus, in the recommended procedure, the E-modulus of the granular layer changes with aircraft loading type, even for the same AC pavement feature. For different combinations of granular base and subbase layers, the following procedures should be used:

a. Granular Base Without Subbase: Use Figure B-36 to determine the E-modulus of the granular base for a given aircraft type.

b. Granular Base and Subbase with CBR $\geq$ 30: Combine total thickness of base and subbase and determine single E-modulus using Figure B-36.

c. Granular Base and Subbase with CBR < 30: Use Figure B-36 to determine the E-modulus of the granular base. Determine the E-modulus of the granular subbase using the relationship

$$E \text{ (psi)} = 1500 \text{ CBR}$$

but not to exceed the E-modulus of the base.

Example: An AC pavement is composed of a 5-inch AC, a 10-inch granular base with CBR 80, and an 8-inch granular subbase with CBR 25. Determine the E-moduli for the granular base and subbase for the four different types of aircraft loads. Assume that using the procedure, the E-modulus of the AC layer has been determined to be 500,000 psi.

a. The granular subbase has a CBR of 25 < 30; thus, the E-modulus of the subbase is

$$E = 1500 \times 25 = 37{,}500 \text{ psi}$$

for all aircraft types.

b. For the base layer, using Figure B-36, the following values are obtained:

	Aircraft Type			
	A	B	C	D
E-modulus (psi)	54,000	65,000	78,000	58,000

If the CBR of the subbase is 30 or higher (instead of 25), combine the base and subbase to one layer 18 inches thick and an E-value as determined above.

When using the BISAR program, a Poisson's ratio for all granular materials of 0.35 is assumed.

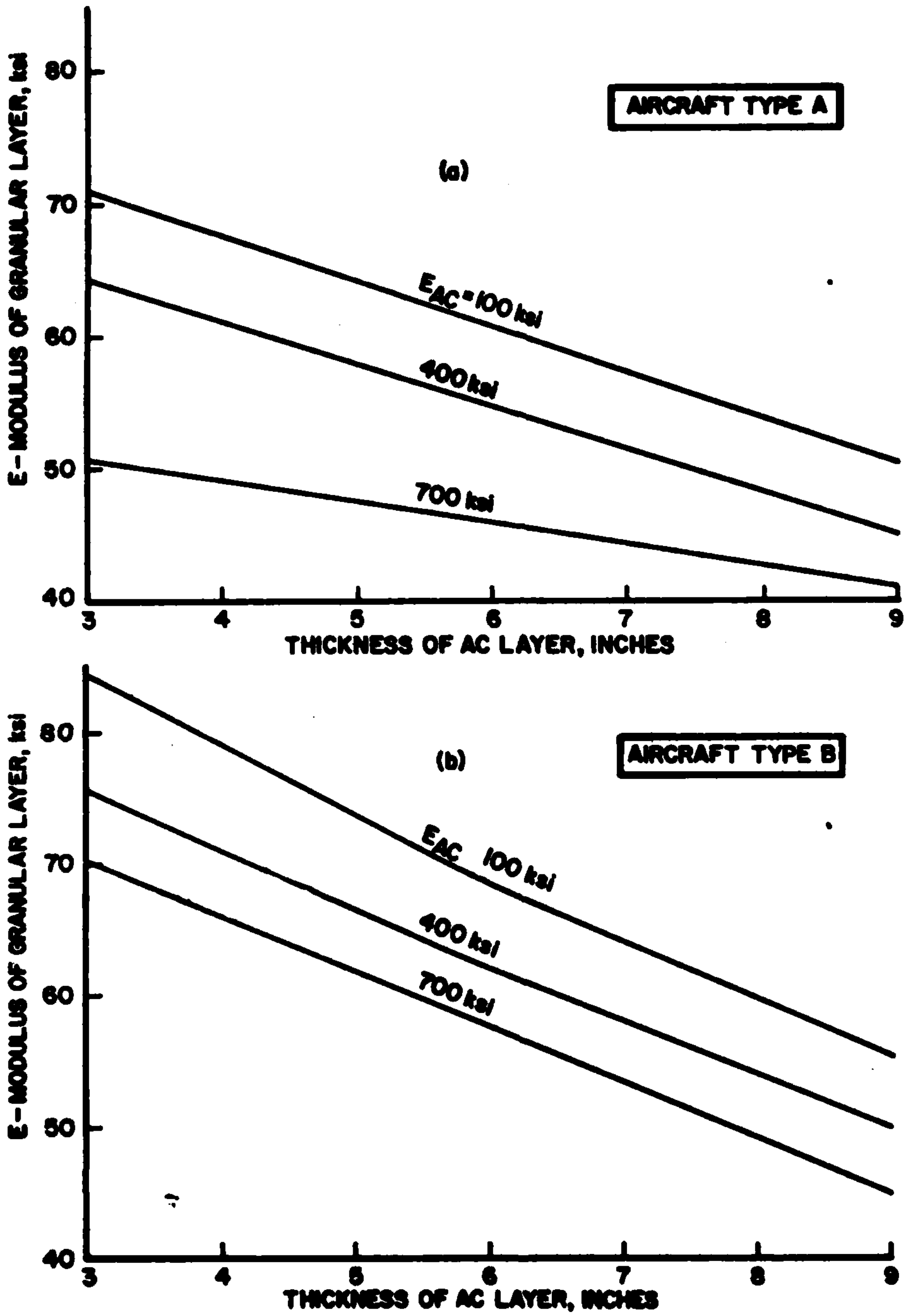
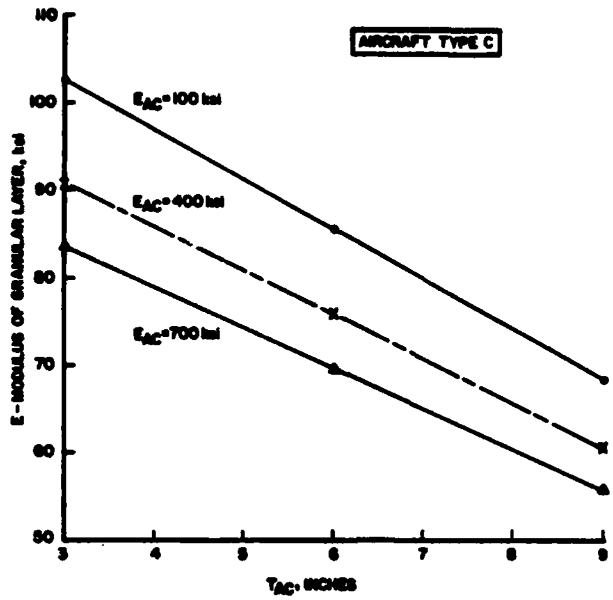


Figure B-36. Illustration To Determine the E-Modulus of a Granular Layer as a Function of the Total Asphalt Thickness and Asphalt Modulus.



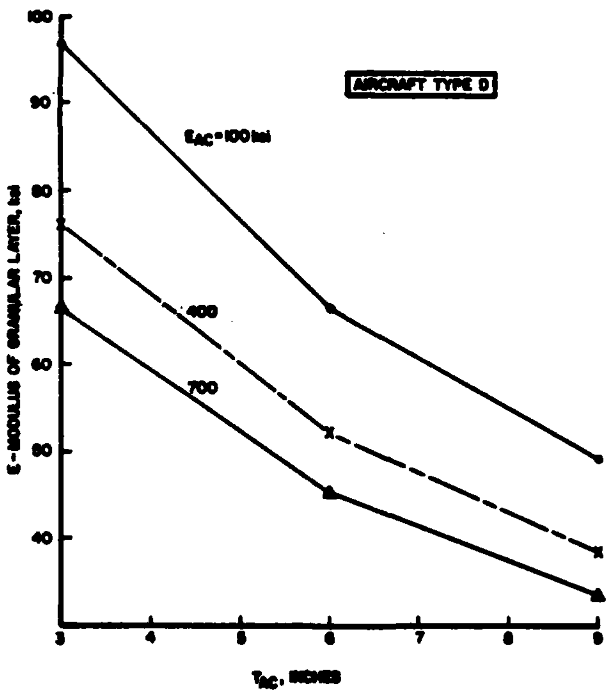


Figure B-36. Illustration to Determine the E-Modulus of a Granular Layer as a Function of the Total Asphalt Thickness and Asphalt Modulus (CONCLUDED).

3. Subgrade Characterization

For all subgrade soils, determine the E-modulus using the relationship:

E (psi) = 1500 CBR

Use a Poisson's ratio of 0.35.

4. Aircraft Loading Characterization

An ESWL was determined for the main gear of each aircraft. The resultant ESWL has the same contact area as each wheel in the gear. The ESWL is computed at a depth of 12 inches, using the U.S. Army Corps of Engineers' one-layer equal deflection method. Table B-3 lists the ESWLs of typical aircraft for the analysis of AC pavements.

5. Procedure Outline

a. Determine the E-modulus of the AC layer based on the layer thickness, the mean annual solar radiation, and the mean annual air temperature.

b. Determine the E-modulus of the granular base using Figure B-36 according to aircraft loading type as given in Table B-3.

c. Determine the E-modulus of the granular subbase using the relation E = 1500 CBR if the CBR is less than 30. If CBR is equal to or greater than 30, combine base and subbase into one layer and determine the E-modulus according to Step 2 above.

d. Determine the E-modulus of the subgrade, using the relation E = 1500 x CBR.

e. Determine the ESWL for a given aircraft from Table B-3.

f. Use a Poisson's ratio of 0.35 for all materials and subgrade.

g. Using the BISAR computer program (Reference 10), compute the surface deflection under the load, the vertical stress at the top of the base, the radial strain at the bottom of the AC layer, and the vertical strain at the top of the subgrade.

h. If the pavement contains a Cement Treated Base (CTB), assume an E-modulus of 10^6 psi and a Poisson's ratio of 0.35, and compute the radial stress at the bottom of the CTB layer.

C. AC/PCC PAVEMENTS

1. Procedure Outline

The procedure used to analyze AC overlays over PCC pavements is provided in Volume VII of this report (Reference 7). The procedure is illustrated by the following example:

Aircraft = DC9

Asphalt overlay = 5 inches

PCC slab - 10 inches

Total surface thickness = 15 inches

Modulus of subgrade reaction (K) = 300 pci

a. Compute percent AC of total surface thickness = 5/15 x 100 = 33.3 percent.

b. Compute a stress correction factor (y) using the equation:

$$Y = 1.00 + 0.0143 \quad X$$

where:

Y = stress at bottom of concrete slab with asphalt overlay divided by stress at bottom of a concrete slab with thickness equal to total pavement thickness (asphalt overlay plus concrete slab).

X = percent asphalt thickness of total thickness (asphalt overlay plus concrete slab).

For the example above:

$$Y = 1.00 + 0.0143 \times 33.3$$

$$Y = 1.976$$

c. Compute the maximum free edge stress for a 15-inch (total thickness) slab, using the appropriate chart in Figure B-33.

$$\sigma_e = 380 \text{ psi}$$

d. Compute the actual stress at the bottom of the slab for a 5-inch overlay over a 10-inch concrete slab as follows:

$$e_{actual} = y \times \sigma_e$$

$$= 1.476 \times 380 = 560 \text{ psi}$$

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